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THESIS

THE INFLUENCE OF OIL CONTAMINATION ON THE NUCLEATE POOL-BOILING BEHAVIOR OF R-114 FROM A STRUCTURED SURFACE

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March 1985

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#20 ABSTRACT (Continued)

of the heat-transfer coefficient of the High Flux surface at heat fluxes less than 30 kW/m^2 and up to an 80 percent reduction at heat fluxes above 30 kW/m^2 with greater than 6 percent oil. Under all conditions, the High Flux coated tube outperformed the smooth copper tube.

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The Influence of Oil Contamination on the Nucleate Pool-Boiling Behavior of R-114 from a Structured Surface

by

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ABSTRACT

The external nucleate pool-boiling heat-transfer coefficient of a horizontal smooth copper tube in R-114-oil mixtures (0 to 10 percent oil) was measured for heat fluxes from 1 to 100 kW/m^2 at two different saturation temperatures (-2.2 °C and 6.7 °C). A copper-nickel tube coated with the Union Carbide "High Flux" coating was similarly tested. The High Flux coating was found to improve the heat-transfer coefficient by at least a factor of 7 in oil-free R-114. Oil resulted in about a 20 percent reduction of the heat-transfer coefficient of the High Flux surface at heat fluxes less than 30 kW/m^2 and up to an 80 percent reduction at heat fluxes above 30 kW/m^2 with greater than 6 percent oil. Under all conditions, the High Flux coated tube outperformed the smooth copper tube.

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I. INTRODUCTION

A. BACKGROUND

The U.S. Navy currently uses refrigerant R-114 in centrifugal chilled-water air-conditioning plants aboard submarines and surface ships. The Navy hopes to reduce the size of these units and increase their performance by using enhanced evaporator and condenser surfaces. An experiment by Arai et al. [Ref. 1] produced a prototype 200-Ton R-12 centrifugal water. chiller that was 28 percent shorter in length and had a 50-70 percent improvement in the overall heat-transfer coefficient by employing the enhanced surface "Thermoexcel E" made by the Hitachi Company. Comparisons of various enhanced commercial tubes by Yilmaz and Westwater [Ref. 2], Marto and Lepere [Ref. 3], and Carnavos [Ref. 4] for various refrigerants other than R-114 indicated that a porous-coating-enhanced surface, such as Union Carbide's "High Flux," will exhibit the best boiling heat-transfer performance in a pure refrigerant.

The High Flux surface (see Figure 1.1) consists of a sintered metallic matrix bonded to a metallic substrate. The surface is produced by coating a smooth tube with a binder-solvent mixture and then applying a mixture of metal and braze alloy powder; the tube is placed in a furnace to evaporate the solvent, binder, and melt braze alloy thus forming a porous structure having multiple reentrant cavities to enhance nucleation. [Ref. 5]

Since the High Flux surface will be employed in a refrigeration unit using an oil-lubricated, hermetically-sealed, compressor, some amount of oil is always present in the evaporator. Studies by Henrici and Hesse [Ref. 6] for

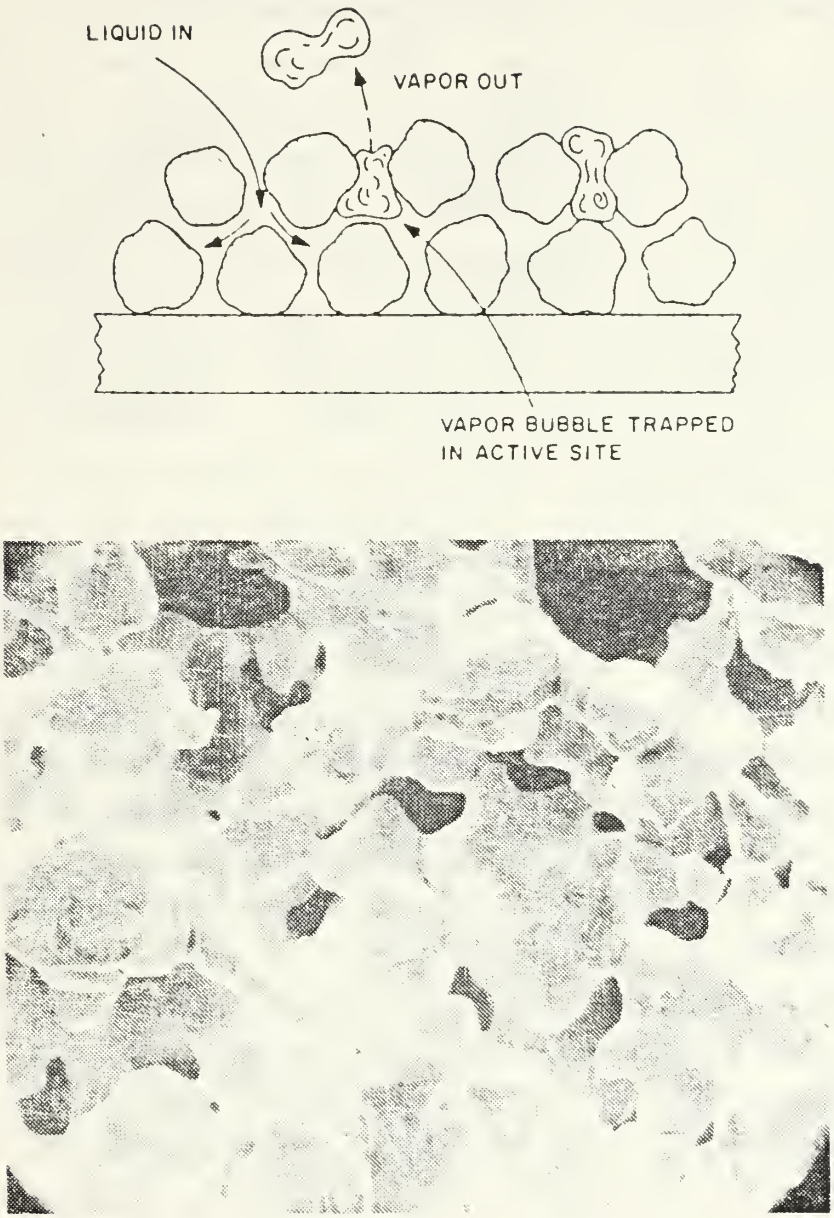


Figure 1.1. Schematic and Scanning Electron Micrograph (500x) of High Flux Surface.

smooth tubes and Stephan [Ref. 7] for the Gewa-T surface (manufactured by the Wieland Company) in R-114-oil mixtures indicate that the heat-transfer coefficient of enhanced surfaces can be significantly altered by oil.

Experimental data showing the effect of oil concentration on the heat-transfer coefficient of the High Flux surface in R-114 are lacking, thus motivating the present investigation. This investigation was funded by the David W. Taylor Naval Ship Research and Development Center. Details of the experimental apparatus are described by Karasabun [Ref. 8]. The smooth copper tubes were supplied by the Wieland Company. The High Flux coated copper-nickel tubes were supplied by the Union Carbide Corporation.

B. THESIS OBJECTIVES

The objectives of this thesis are:

1. Take boiling data on a smooth tube in R-114 with and without oil for comparison with the data of other researchers, and to provide baseline data for evaluating the boiling performance of the High Flux tube.
2. Take boiling data on a High Flux tube for various oil concentrations (0 to 10 percent by mass).
3. Study the effect of saturation temperature on the R-114 boiling behavior.
4. Attempt to sample oil locally in the near vicinity of a tube to investigate the possibility of an oil concentration gradient around the tube during operation.

II. REVIEW OF REFRIGERANT-OIL MIXTURE BEHAVIOR

A. NUCLEATE BOILING OF REFRIGERANT-OIL MIXTURES FROM SMOOTH TUBES

In 1963, Stephan [Ref. 9] published a milestone paper on the influence of oil on the boiling heat transfer of R-12. The effects he noted have been observed in most refrigerants, including R-114. In 1972, Henrici and Hesse [Ref. 6] updated Stephan's work for R-114-oil mixtures boiling from a smooth copper tube. Figures 2.1 and 2.2 summarize Henrici and Hesse's results. Figure 2.1 shows that oil generally lowers the heat-transfer coefficient, and that at high heat fluxes and high oil concentrations (10 percent), the effect grows more pronounced (slope decreases). Figure 2.2 shows that at some oil/heat flux combinations, the heat-transfer coefficient may actually be improved by the addition of oil. Chongrungreong and Sauer [Ref. 10] suggest that the heat-transfer behavior of refrigerant-oil mixtures can be attributed to 5 major factors: 1) the physical properties of the refrigerant-oil mixture, 2) the saturation temperature (or boiling pressure), 3) the tube diameter, 4) the surface condition of the tube (roughness), and 5) the hydrostatic liquid head above the tube.

1. Physical Properties

Refrigerant-oil mixtures have significantly different physical properties than pure refrigerants. Jensen and Jackman [Ref. 11] report that density and specific heat behave ideally in refrigerant-oil mixtures, but that viscosity and surface tension do not. Ideal behavior of refrigerant-oil mixture density and specific

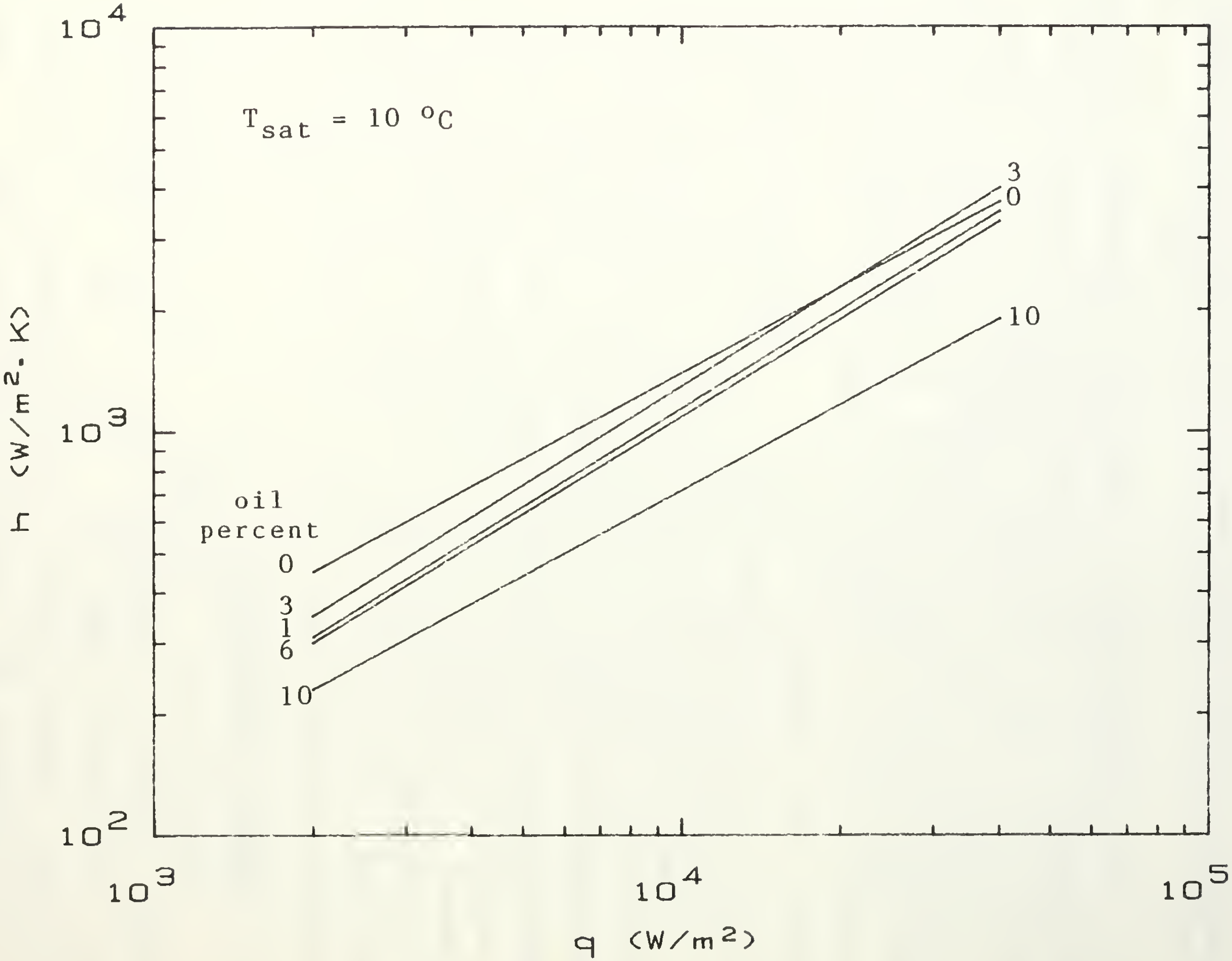


Figure 2.1. Effect of Oil on Boiling Coefficient of R-114 (from Ref. 6).

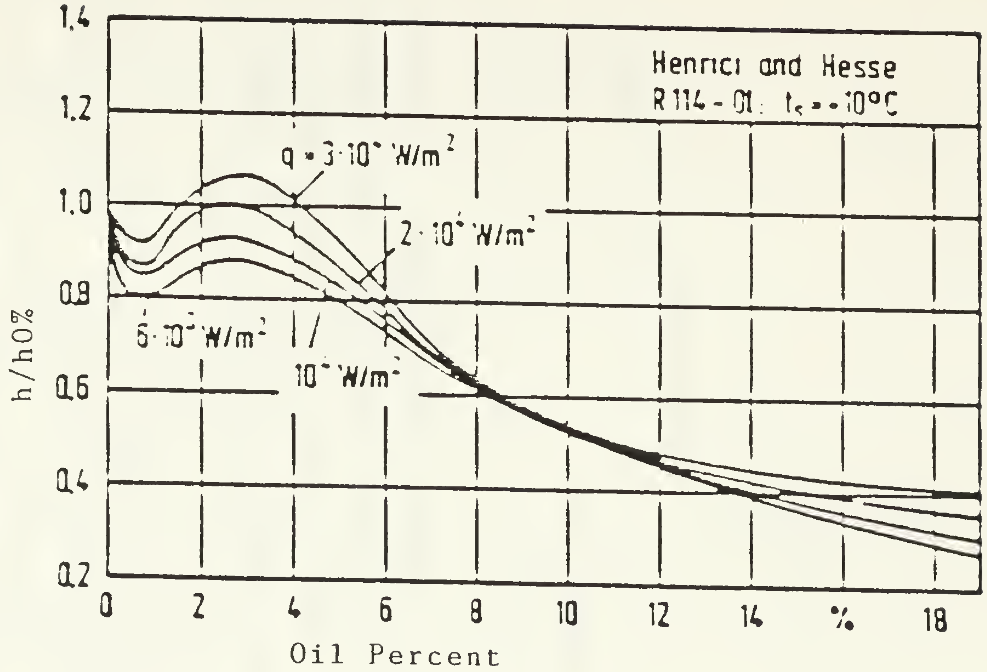


Figure 2.2 Variation of Heat-Transfer Coefficient of R-114-Oil Mixtures (from Ref. 13).

heat does not mean linear behavior. The governing equations are:

$$\frac{1}{\rho_m} = \frac{C}{\rho_{o\ell}} - \frac{1 - C}{\rho_{r\ell}} \tag{2.1}$$

and

$$c_{pm} = (1 - C)\ c_{pr\ell} + C\ c_{po\ell} \tag{2.2}$$

where

ρ = density

C = oil concentration

c_p = specific heat

subscripts:

ℓ = liquid

m = mixture

o = oil

r = refrigerant

Jensen and Jackman report that current refrigerant-oil mixture viscosity equations substantially underpredicted their experimental data. No predictive equation has been suggested for the surface tension of refrigerant-oil mixtures, though Jensen and Jackman developed a correlation for R-113-oil mixtures.

Henrici and Hesse [Ref. 6] experimentally determined the surface tension for the R-114-oil mixtures that they used in their 1971 experiment. As shown in Figure 2.3, the surface tension of the mixture first decreased up to an oil concentration of 2.5 percent, and then increased continuously with increasing oil concentration. This type of nonlinear behavior makes explaining the change in heat-transfer coefficient of refrigerant-oil mixtures, due to the changing physical properties of these mixtures, both difficult, and

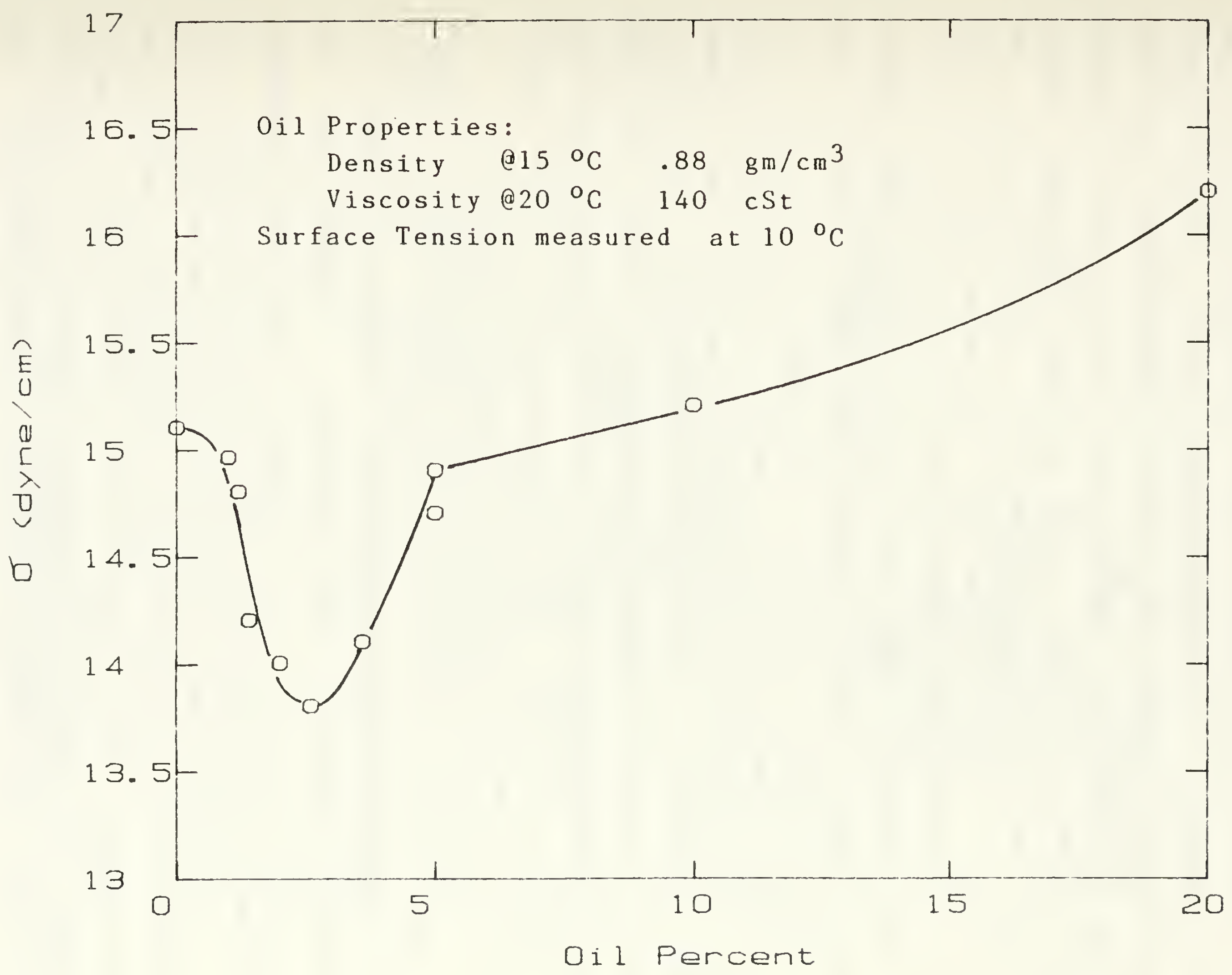


Figure 2.3 Surface-Tension Variation of R-114-Oil Mixtures (from Ref. 6).

possibly non-general. The behavior of refrigerant-oil mixtures is specific to the particular mixture components, and may be dependent upon the kind of oil being used. Some qualitative consequences of adding oil to a refrigerant, however, can be noted.

The most observable result of adding oil to refrigerants is foaming. Oil concentrations above 1 percent result in significant amounts of foaming from nucleate boiling. The foam bubbles form because the R-114 in the R-114-oil mixture is more volatile than oil and vaporizes first, creating a gas bubble surrounded by an oil-rich layer (see Figure 2.4). Since the bubbles are coated with oil film with a higher surface tension than the bulk liquid and a have lower density, they rise to the top of the liquid. Because of their surface tension, the bubbles build up on the liquid surface to produce a foam layer.

This foaming action, which is most pronounced between 1-10 percent oil concentration [Ref. 6], may affect the heat transfer of tube bundles significantly. For single tubes, it is the oil concentration gradient which would seem to play the major role, since the foam rises away from the tube surface and could only interact with the tube as it sweeps by it from the bottom to the top of the tube.

The general decrease in the heat-transfer coefficient upon adding oil to pure refrigerants (recall Figure 2.1) is subject to many explanations. Thome [Ref. 14], in an extensive review of the literature, reports that the first explanation for the decrease in the heat-transfer coefficient of mixtures was presented by Van Wijk et al. in 1956. The effect was explained as being the result of the evaporation of the more-volatile components, leaving an oil-rich layer with a higher local boiling point, which increases the amount of superheat required to continue vaporization and bubble growth, thus reducing the

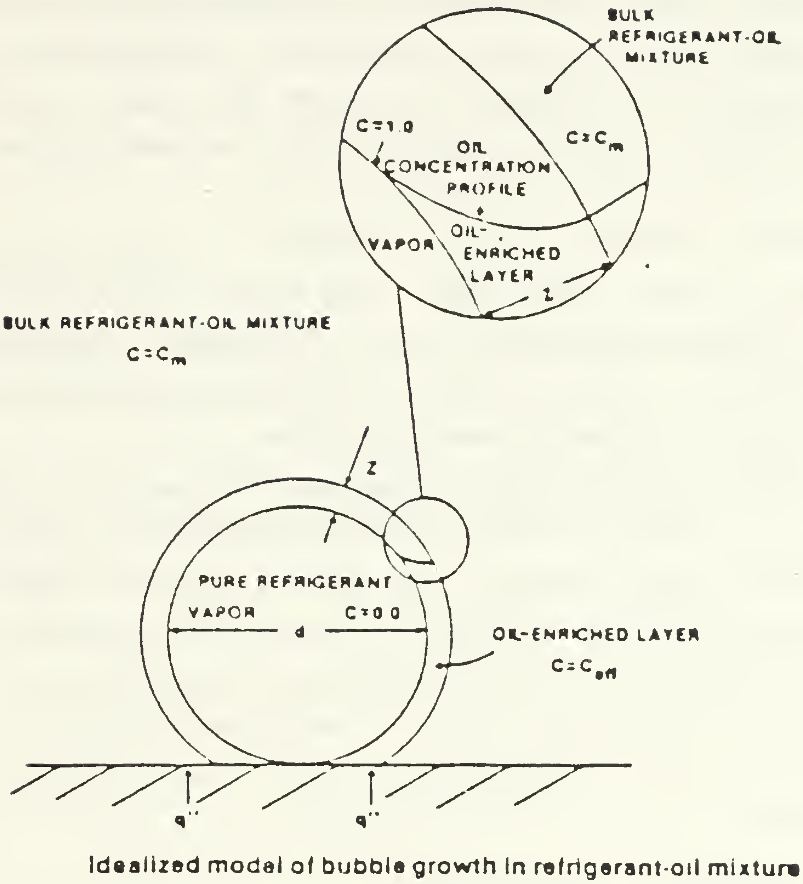


Figure 2.4 Oil Concentration Gradient in a Bubble in Refrigerant-Oil Mixtures (from Ref. 11).

heat-transfer coefficient. Stephan and Preusser [Ref. 12] demonstrated conclusively that the work of formation of bubbles in a mixture is greater than in an equivalent pure fluid. They concluded that the mixture heat-transfer coefficient is lower than for the equivalent pure fluid because of the resulting decrease in the bubble population. Any variation from a decreasing mixture heat-transfer coefficent (like Henrici and Hesse show in Figure 2.2) is attributed by Stephan [Ref. 13] to the non-linear variation of the physical properties. Stephan proposes that the plot of surface tension (Figure 2.3), along with thermal-property variations, accounts for the anomalous rise in the heat-transfer coefficient between 3-6 percent oil concentration. Chongrongeong and Sauer [Ref. 10] state that it is the rate of heat diffusion, governed by the thermal properties of the oil-rich layer, that limits the bubble growth and that the surface-tension effects are neglible.

Thome [Ref. 14] proposes that all of the above factors, as well as the viscosity variation, are important in explaining the rise in the heat-transfer coefficient for some refrigerant-oil mixture and heat-flux combinations.

In summary, all researchers agree that the physical and thermal properties of a refrigerant-oil mixture are important factors in explaining the heat-transfer behavior of mixtures.

2. Saturation Temperature

It has long been noted that increased saturation temperature (i.e., increased boiling pressure) increases the boiling heat-transfer coefficient of surfaces in refrigerant-oil mixtures. In 1963, Stephan [Ref. 9] found that at high oil concentrations, the heat-transfer coefficient of refrigerant-oil mixtures becomes constant with respect to the saturation temperature. Stephan proposed

that this is because the addition of oil to a refrigerant introduces a large diffusion resistance, and that since the velocity of diffusion is almost independent of temperature, so should the heat-transfer coefficient become independent of temperature at high oil concentration. Figure 2.5 shows Henrici and Hesse's data on the effect of oil and saturation temperature in R-114. With no oil, the effect of raising the saturation temperature is seen to be a rise in the heat-transfer coefficient. With oil, raising the saturation temperature is seen to cause a slight drop in the heat-transfer coefficient. This effect has not been explained yet.

3. Tube Diameter

Cornwell, Schuller, and Einarsson [Ref. 15] found that for smooth tube diameters from 6 mm to 30 mm, the nucleate pool boiling heat-transfer coefficient in pure refrigerants falls with increasing diameter. The effect of tube diameter was correlated by:

$$Nu = C\ Re^{2/3} \tag{2.3}$$

where

$$Re = \frac{q\ D}{h_{fg}\ \mu}$$

$$Nu = \frac{h\ D}{k}$$

C = 150 for refrigerants

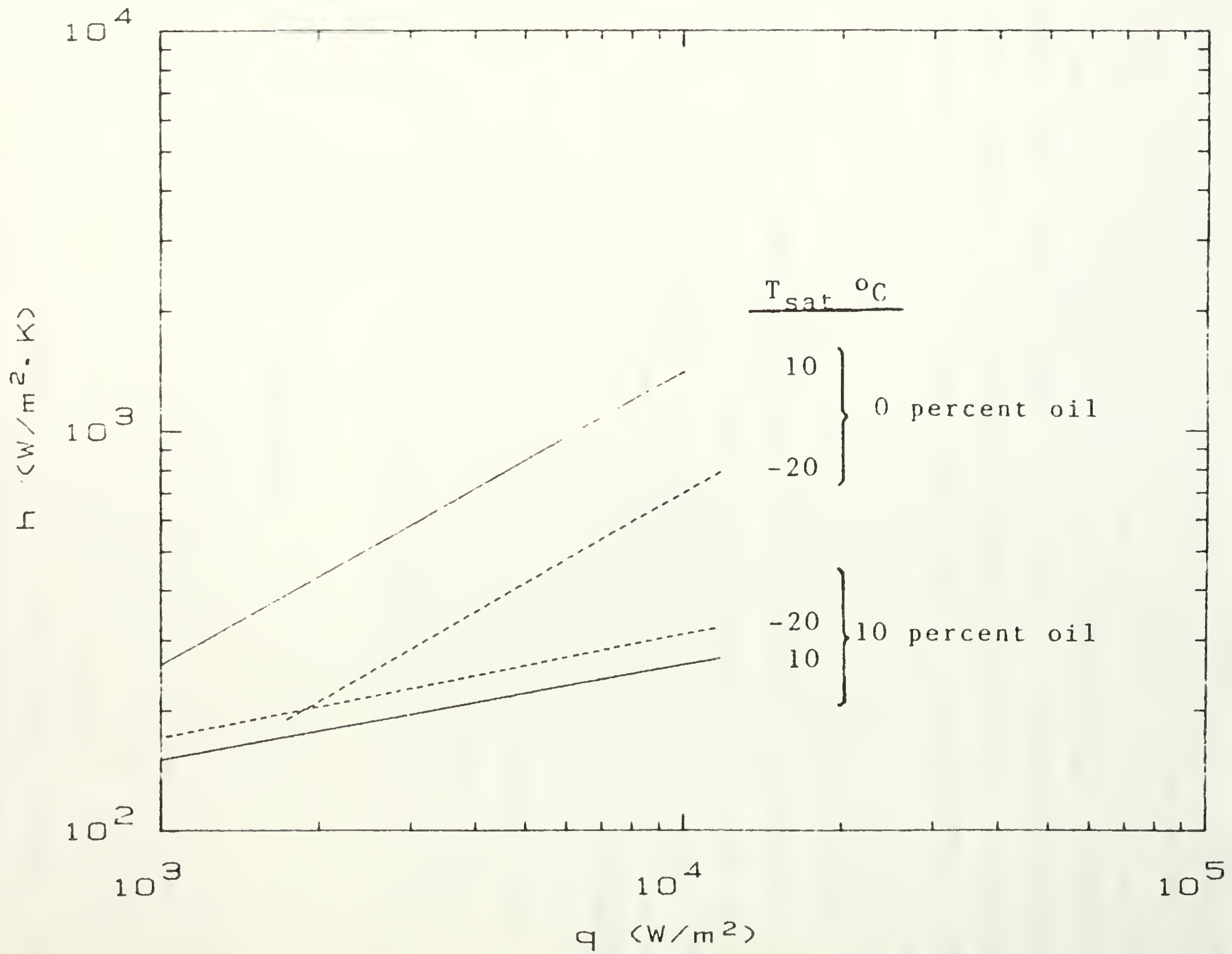


Figure 2.5 Effect of Saturation Temperature on R-114-Oil Mixtures (from Ref. 6).

Since equation (2.3) depends on physical parameters, the effect of oil could be significant. No known measurements of the effect of tube diameter in refrigerant-oil mixtures have, as yet, been performed.

4. Surface Condition

Several researchers [Ref. 16, 17, 18] have investigated the effects of surface roughness on the heat transfer of pure refrigerants. As surface roughness increases, the heat-transfer coefficient was found to increase due to increased nucleation. Nishikawa [Ref. 18] reported the effect of a variety of surface roughnesses in pure R-114 over a range of pressures from 0.294 MPa (42 psi) to 2.94 MPa (420 psi).

5. Hydrostatic Effect

The liquid column above the boiling surface may generate large static pressures which will increase the boiling point. For R-114 at 0 ^{o}C (32 ^{o}F), a 0.3 m (1 ft) liquid head will raise the saturation temperature about 5 ^{o}C (9 ^{o}F). In large machines, this may be a significant effect. However, for small experimental apparatuses, the effect is negligible.

B. NUCLEATE BOILING OF REFRIGERANT-OIL MIXTURES FROM ENHANCED SURFACES

Webb [Ref. 19], in an extensive review of the evolution of enhanced surface geometries, notes that the ability of roughness to improve nucleate boiling performance has been known for over 50 years. However, it was not until 1968 that the first commercial enchanced surface was patented [Ref. 20]. Since then, the number of commercial enhanced surfaces has dramatically increased as the understanding of

their design and operation has grown. Of the many possible methods for heat-transfer enhancement, two areas are currently being commercially developed: 1) fins and surfaces with reentrant cavities, and 2) porous coatings.

1. Fins and Surfaces with Reentrant Cavities

The ability of surface abrasion, open grooves, and fins to improve the heat-transfer performance of a smooth surface was first studied in the 1930's. The main difficulty with using surface abrasion to improve the heat-transfer performance is that fouling of the surface eventually returns the performance to that of a non-abraded surface. Studies in the 1950's and 1960's centered on fins. Recent comparative studies for refrigerants by Carnavos [Ref. 4] and Yilmaz and Westwater [Ref. 2] found that fins and grooves result in a 50-100 percent permament improvement in the heat-transfer performance compared to a smooth plain tube in the same refrigerant. Webb [Ref. 19], in his literature review, describes how researchers in the early 1960's found methods to improve the performance of fins by creating reentrant cavities on their surfaces. Reentrant cavities, such as shown in Figure 2.6, act as very stable nucleation sites and thereby enhance the heat-transfer performance. For a cavity to function as a nucleation site and remain active, even after the surface is subcooled, the mouth diameter (D) must fall within a critical range. Also, the cavity must have a reentrant shape with a maximum reentrant angle (θ). The optimum mouth diameter (D) and reentrant angle (θ) are functions of the fluid properties.

The Gewa-T surface, patented in 1979 (manufactured by the Wieland Company), and the Thermoexcel-E surface, patented in 1980 (manufactured by the Hitachi Company), are two commercial surfaces which use modified fin shapes to form the necessary reentrant cavities. Figure 2.7 shows the

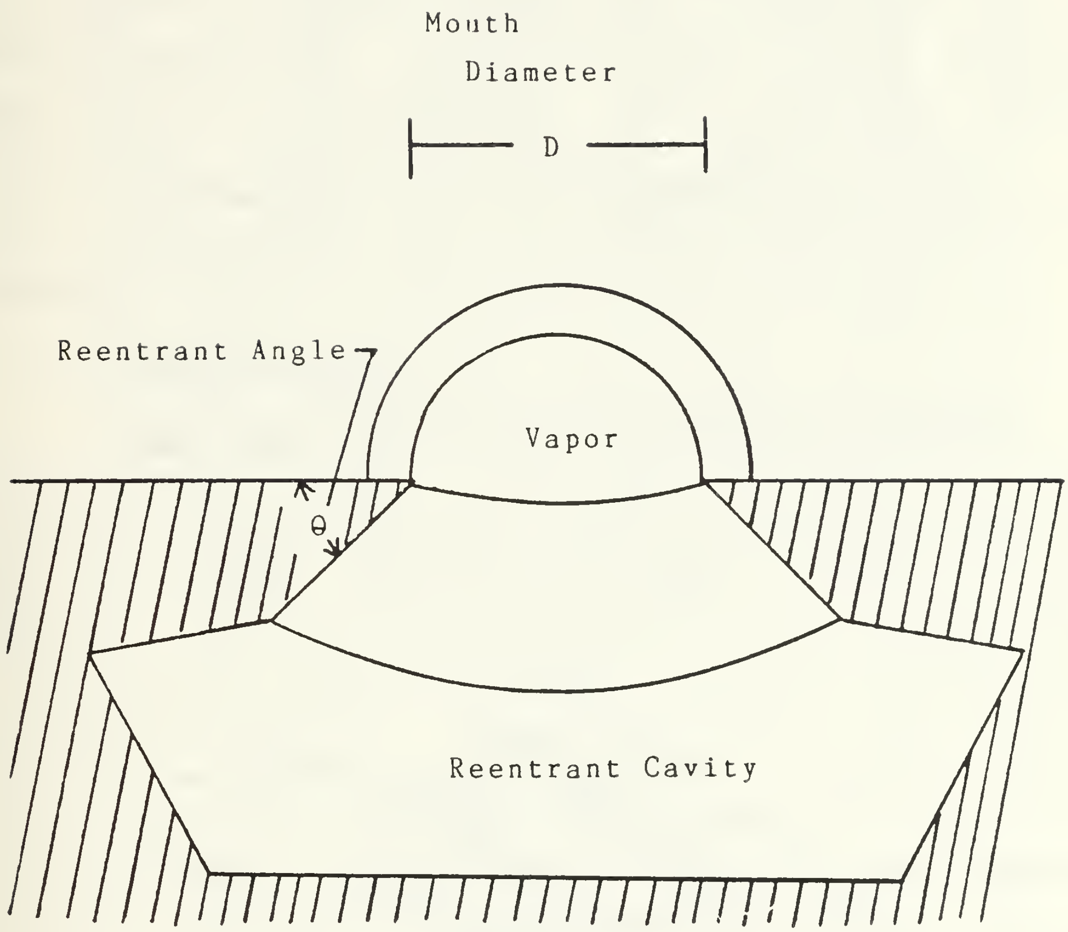
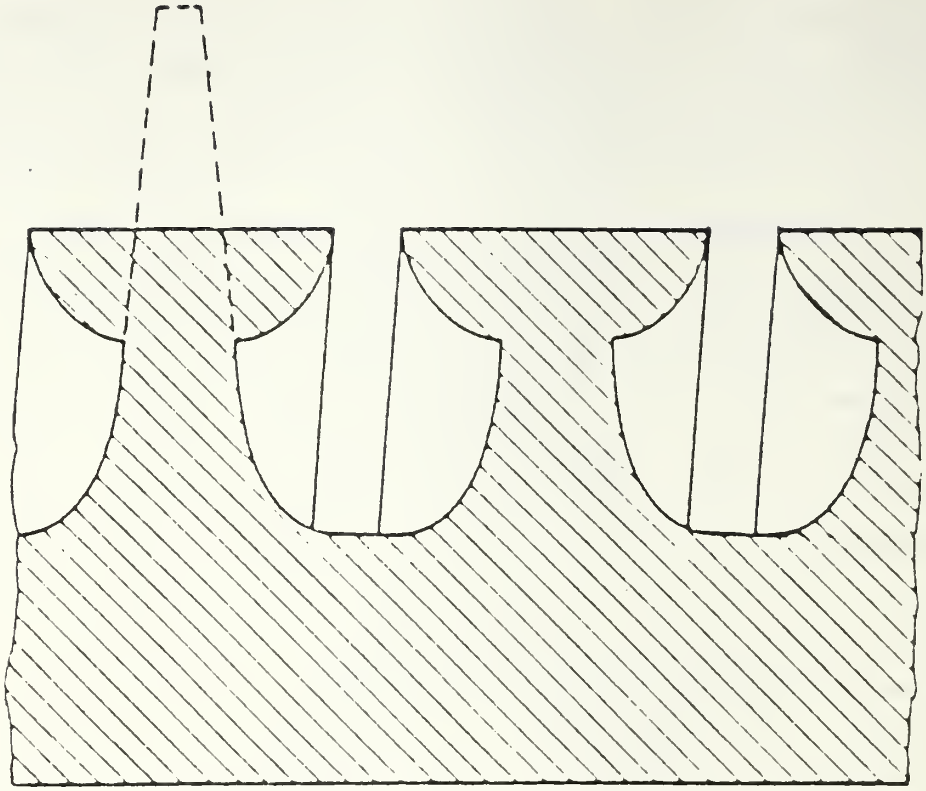
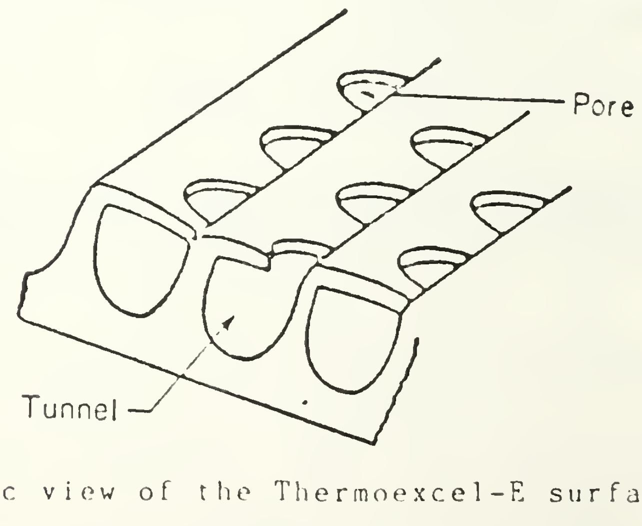


Figure 2.6 Reentrant Cavity Geometry Factors.



(a) Schematic cross section of the Gewa-T surface



(b) Schematic view of the Thermoexcel-E surface

Figure 2.7 Surface Details of Gewa-T and Thermoexcel-E Reentrant Surfaces.

details of these tube surfaces. Carnavos [Ref. 4] found that in pure R-11, the Gewa-T surface outperformed a plain tube by 100-200 percent and the Thermoexcel-E surface outperformed a plain tube by 300-400 percent. Curves 1-5 of Figure 2.8 show the relative improvement in the boiling heat-transfer performance of R-11 that can be achieved by using mechanically produced reentrant cavities. Work continues to optimize these types of surfaces for the various refrigerants in use commercially. Both tubes have been tested in refrigerant-oil mixtures and did not show a significant decrease in performance [Ref. 1 and 7]. The cost of these surfaces is not significantly higher than for smooth plain tubes, and the performance improvement is dramatic.

2. Porous Coatings

The second major type of enhanced surface is the porous boiling surface. Webb [Ref. 19] details the various production improvements and coating variations that have been made to the original 1968 patent by Milton of Union Carbide. The key to the performance of the porous coatings is their small reentrant cavities, which are interconnected by substrate tunnels. The particles used to make the coatings are usually copper or aluminum. According to Webb, researchers have found that the critical variable is the pore size rather than the particle size. Large pores are required for fluids with high surface tension and high thermal conductivity. Small pores are optimum for fluids with low surface tension and low thermal conductivity (like refrigerants). Curve 6 of Figure 2.8 shows the relative performance of the High Flux surface to finned tubes and mechanically produced reentrant surfaces. Carnavos [Ref. 4] found the High Flux surface to be 700-800 percent better than a smooth tube in R-11. No known studies have been

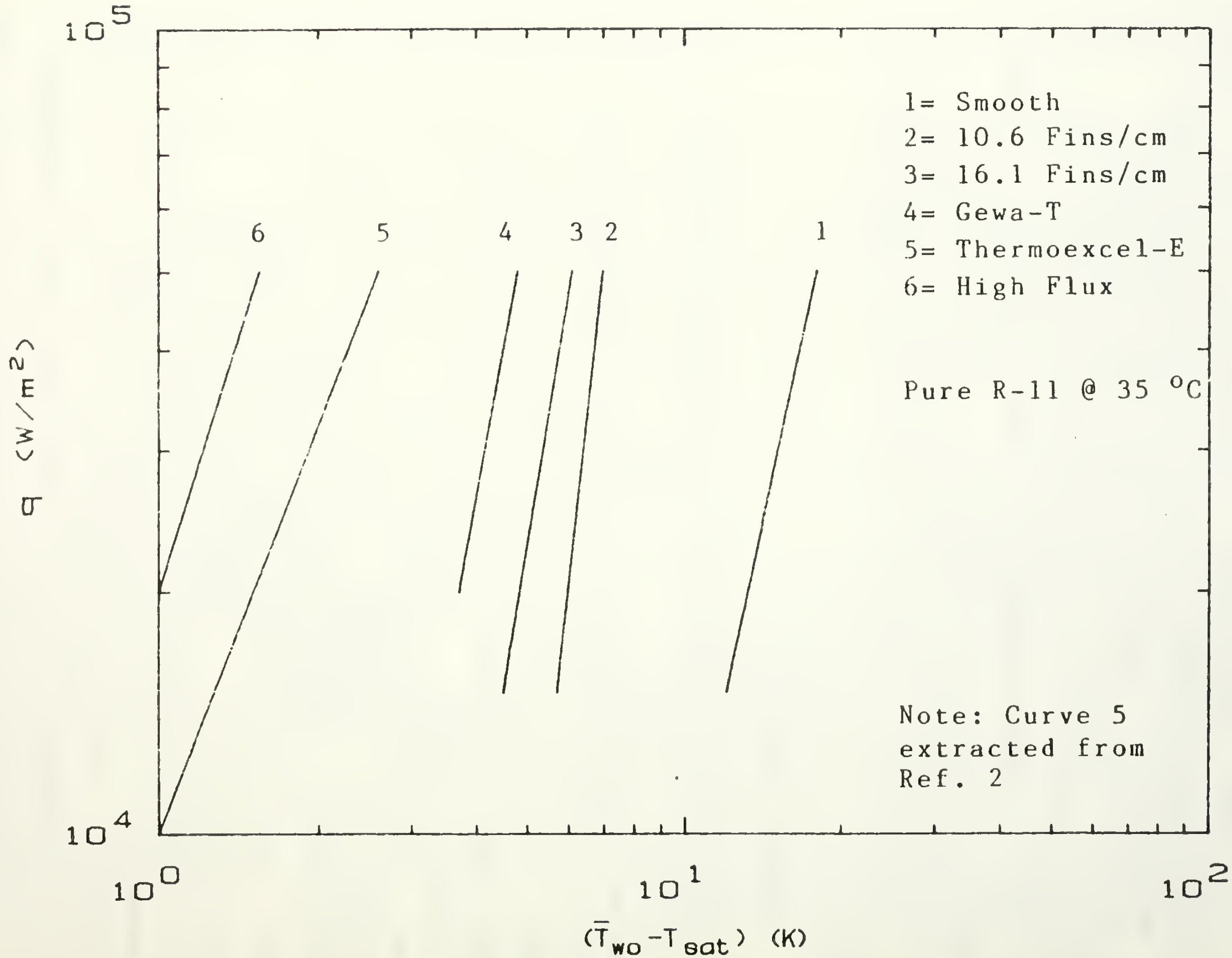


Figure 2.8 Comparison of R-11 Boiling Performance from Various Commercial Surfaces (from Ref. 4).

published on the performance of porous coatings in refrigerant-oil mixtures. Some studies of the heat-transfer performance of porous coatings in pure R-114 and refrigerant-oil mixtures have been made by Union Carbide, but their results are not found in the open literature.

III. DESCRIPTION OF EXPERIMENTAL APPARATUS

A. OVERALL APPARATUS

An overall schematic of the experimental apparatus is shown in Figure 3.1, and a photograph is shown in Figure 3.2. Karasabun [Ref. 8] describes the design, construction, and operation of the apparatus in detail.

The apparatus consists of two Pyrex-glass tees. Liquid R-114 is boiled in glass tee (1) and is condensed in glass tee (2). Gravity drains the condensate from the condenser back to the boiling section. A water-ethylene-glycol mixture at -17 ^{o}C (1 ^{o}F) is pumped through the condenser cooling coil via a computer-controlled valve (VC) to condense the R-114 vapor. The sump (7) that supplies the water-ethylene-glycol mixture is cooled by a 1/2-Ton, R-12 air-conditioning plant.

Valve VC controls the R-114 liquid temperature and pressure. Figure 3.3 is a photograph of valve VC and the computer-controlled motor that operated VC. Opening VC causes more R-114 to condense and lowers the system pressure. Also, it returns more subcooled liquid to the boiling section which lowers the bulk liquid temperature. Since data at many heat fluxes was desired for a constant temperature, it can be seen that changing the heat flux without adjusting VC would change the system pressure and temperature. A computer-controlled valve was thought to be the best way to rapidly return the system to the desired saturation temperature following a heat flux change. Sections III.E and IV.D describe in more detail the computer-controlled valve and the operation of the system with the computer-controlled valve in use.

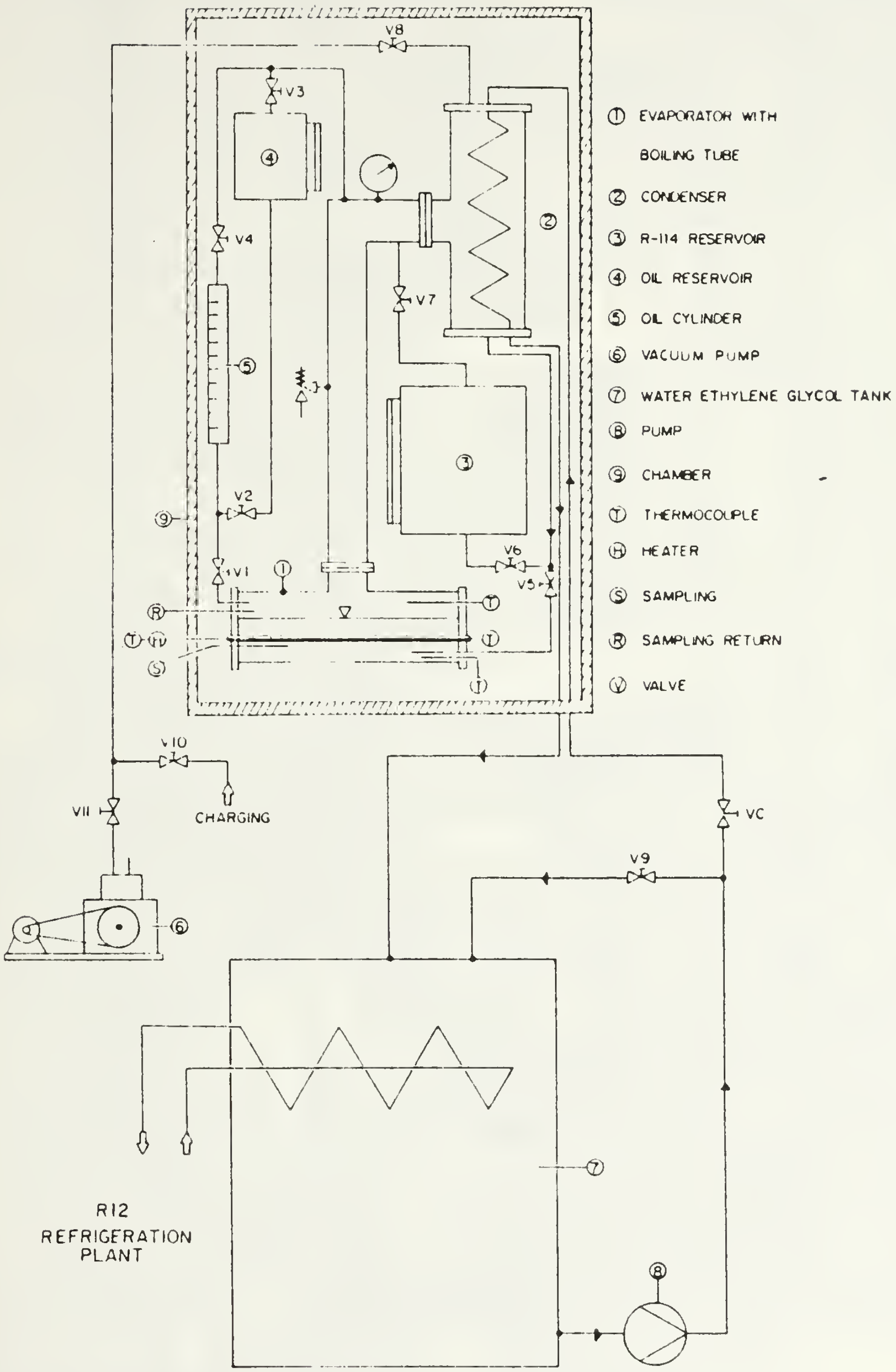


Figure 3.1 Schematic of Experimental Apparatus.

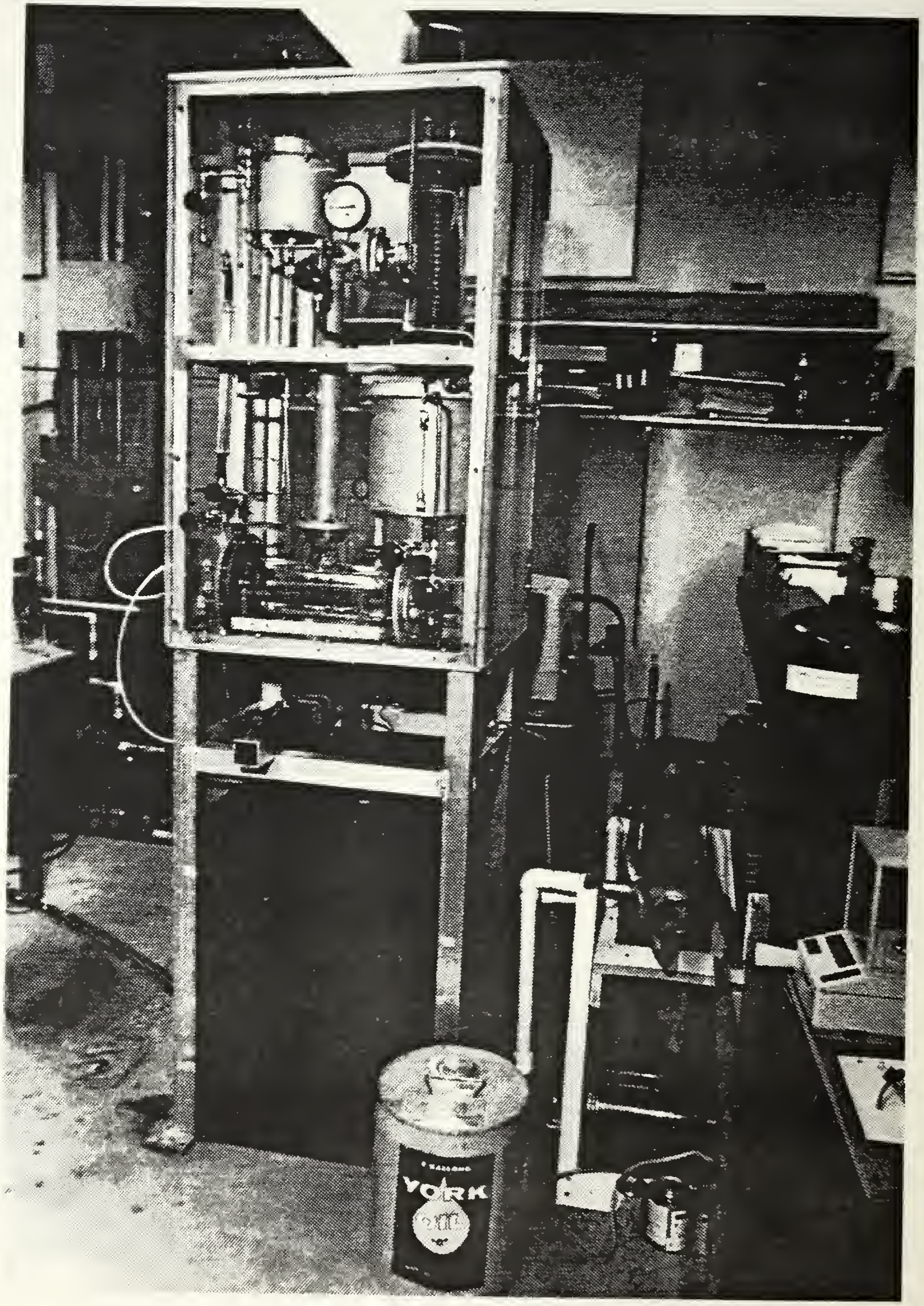
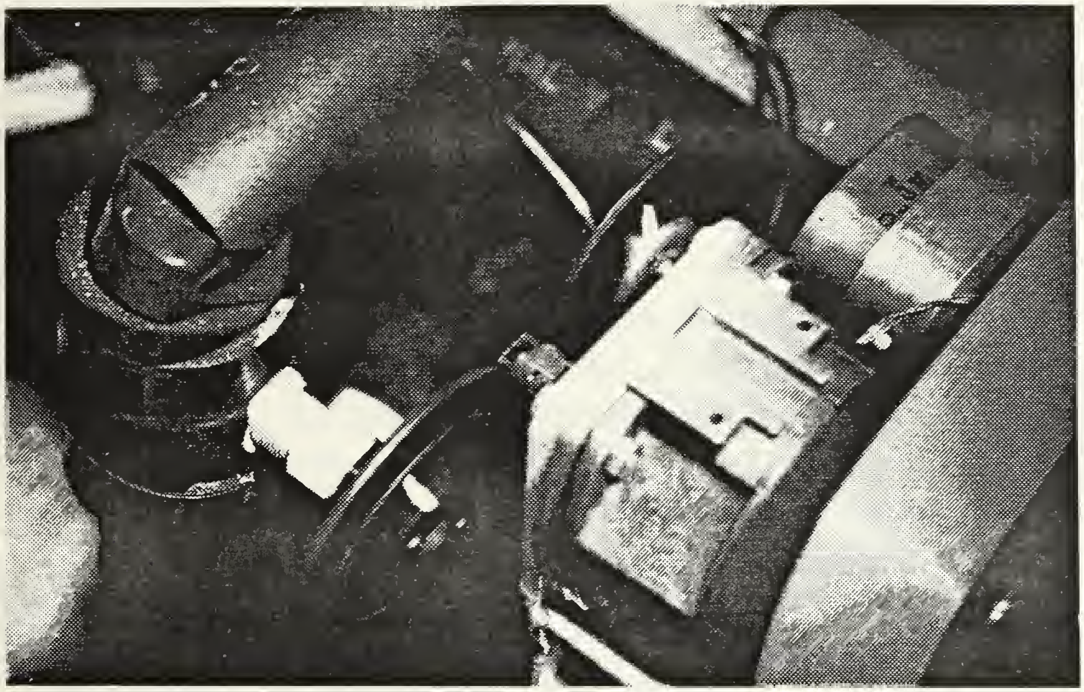


Figure 3.2 Photograph of Experimental Apparatus.



(a) Computer-Controlled Valve.

(b) Computer for Computer-Controlled Valve.

Figure 3.3 Photographs of Computer-Controlled-Valve Equipment.

Oil was added to the liquid R-114 by draining it from a glass oil cylinder (5). The oil cylinder was refilled as needed through valve V-2 from the oil reservoir (4).

Two configurations of boiling tubes were tested. Short boiling tubes were tested to determine the correct assembly procedure to obtain data on the normal 431.8 mm (17 in.) long boiling tubes. The short tubes were cheaper to make, thus more debugging attempts could be made by testing them. Section III.C describes the details of the construction of the short and long test tubes.

B. OIL SAMPLING APPARATUS

Following all data runs, an attempt was made to sample the local oil concentration in the vicinity of a boiling tube. Figure 3.4 shows the oil sampling apparatus. By opening valves S-1, S-2, and S-4, the probe line could be purged, trapping a sample inside a flexible silicon tube that was 30.5 mm (12 in.) long with a 3.16 mm (1/8 in.) inside diameter using pinch clamps. By weighing the sample tube and then boiling off the R-114 leaving behind the oil, the mass percent of oil in the R-114-oil mixture was determined. The mass fraction of oil was calculated by:

$$\text{Mass Fraction} = \frac{m3 - m1}{m2 - m1} \qquad (3.1)$$

where

m1 = mass of sample line

m2 = mass of sample line + R-114 + oil

m3 = mass of sample line + oil (after boiling off R-114)

A Precisa Model 80 electronic mass balance was used to weigh the samples. The Precisa Model 80 is accurate to ± 0.0001 g.

C. BOILING TUBE CONSTRUCTION

1. Short Tubes

Figure 3.5 shows the design of the short tubes. The short tubes were 15.9 mm (5/8 in.) in outer diameter, 12.7 mm (1/2 in.) in inside diameter, and 203.2 mm (8 in.) in length. The short tubes extended 152.4 mm (6 in.) into the liquid R-114 from the left end flange. A 25.4 mm (1 in.) long epoxy plug insulated the right end of the tube. A 1 mm (0.04 in.) thick copper disk behind the epoxy plug was soft soldered in place to act as a pressure barrier. The short tubes were heated by a 500-Watt 240-Volt stainless-steel cartridge heater. The heater was 6.35 mm (1/4 in.) in cuter diameter and 101.6 mm (4 in.) in length.

The first short tube was made from thick-walled copper tubing. This tube was solid oxygen-free, high conductivity (OFHC) copper. Four 1.2 mm (3/64 in.) diameter holes were drilled into the wall of this tube at a diameter of 12.7 mm (1/2 in.) for thermocouple channels. Since this tube was solid, and had no sleeve interface, it did not have an interface resistance. Consequently, it was the reference tube against which all other tubes were compared to determine the amount of contact resistance they had.

Six other short tubes were made. Five were made of soft copper tubing and had sleeves inserted into the tube as indicated in Table 1. Soft soldering of the sleeves to the tubes was determined to yield negligible contact resistance by comparison with the solid tube. The last short tube (7) was made of 90-10 ccpper-nickel and was coated with High Flux over the active 101.6 mm (4 in.) long section. This

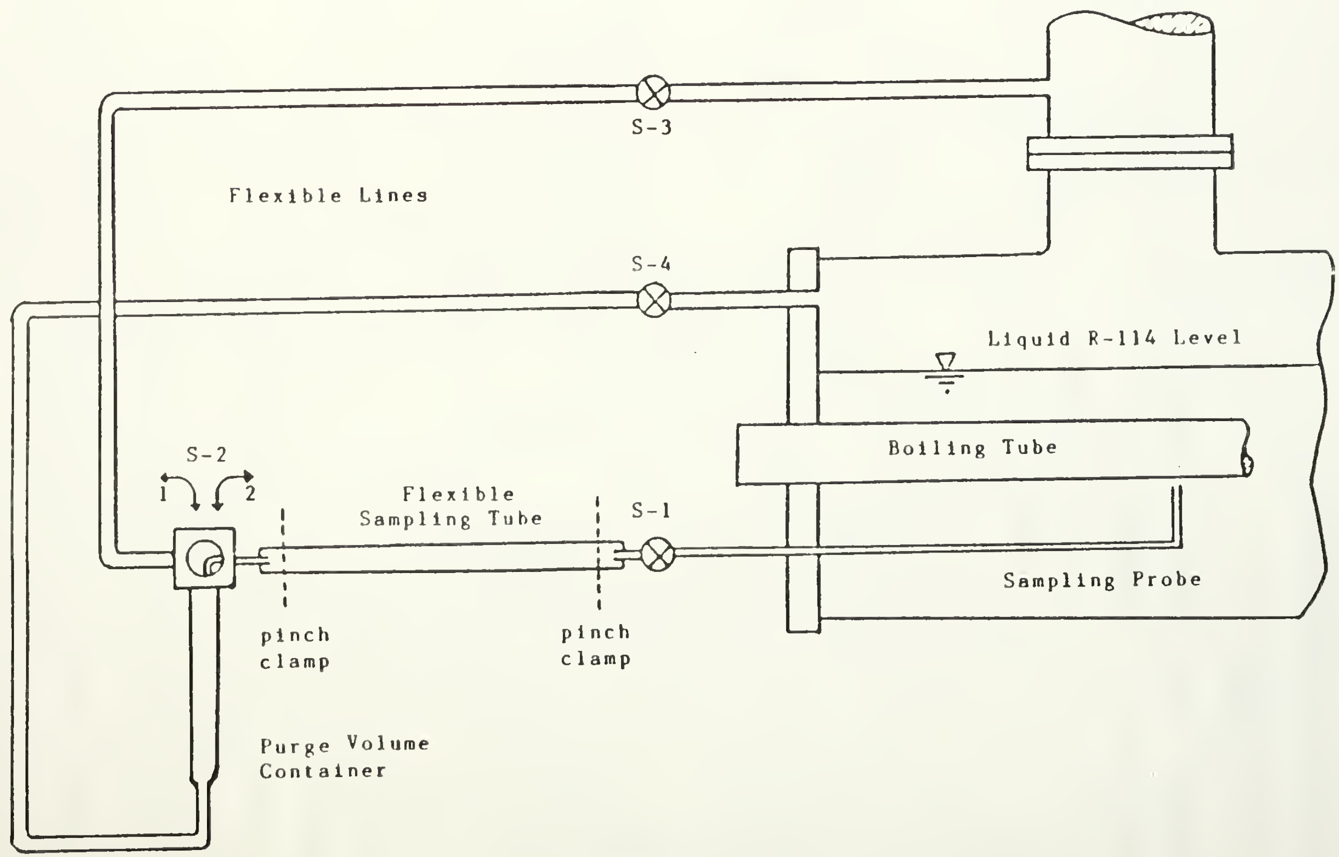
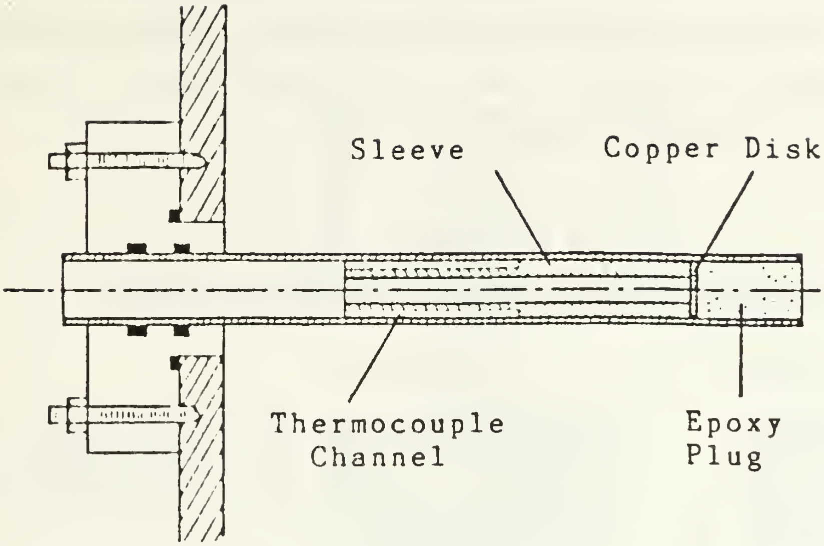
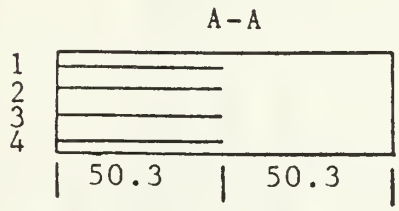


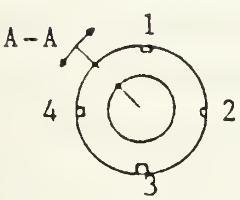
Figure 3.4 Oil Sampling Apparatus.



(a) Sectional view of short tube.



(b) Thermocouple sleeve unwrapped (at section A-A) to show the relative locations of the thermocouple channels (all dimensions in millimeters).



(c) Left-end view of the short tube.

Figure 3.5 Sectional Views of Short Boiling Tube.

tube tested the compatibility of the soft-solder-assembly method with the copper-nickel tube and High Flux coating. Section V.A describes the results of data taken on the short tubes and the selection of the soft-solder method of assembly for the long tubes.

TABLE 1

Summary of Short Tube Assembly Methods

Tube	Surface	Remarks
1	Smooth	Solid, thick-walled tube (reference)
2	Smooth	Slide-fit (0.005 in. clearance)
3	Smooth	Slide-fit (0.002 in. clearance)
4	Smooth	Press-fit (0.004 in. interference)
5	Smooth	Press-fit (0.006 in. interference)
6	Smooth	Soft-soldered
7	High Flux	Soft-soldered

2. Long Tube

Figure 3.6 shows the design of the long boiling tubes. These boiling tubes were 15.9 mm (5/8 in.) in outer diameter, 12.7 mm (1/2 in.) in inside diamter and 431.8 mm (17 in.) in length. The center 203.2 mm (8 in.) was the active test section. For the copper-nickel tube, the center section was the only portion of the tube that was coated with High Flux. The remaining 114.3 mm (4.5 in.) on either side of the center section were smooth and unheated, and did not nucleate under any heat flux or oil condition. Karasabun [Ref. 8] describes how these end-surfaces were treated by the data-reduction program as an extended fin from the center section and how their heat loss was accounted for.

The center section was heated by a 1000-Watt 240-Volt stainless-steel cartidge heater. The heater was 6.35 mm (1/4 in.) in outer diameter and 203.2 mm (8 in.) in length. The heater was surrounded by a copper sleeve with

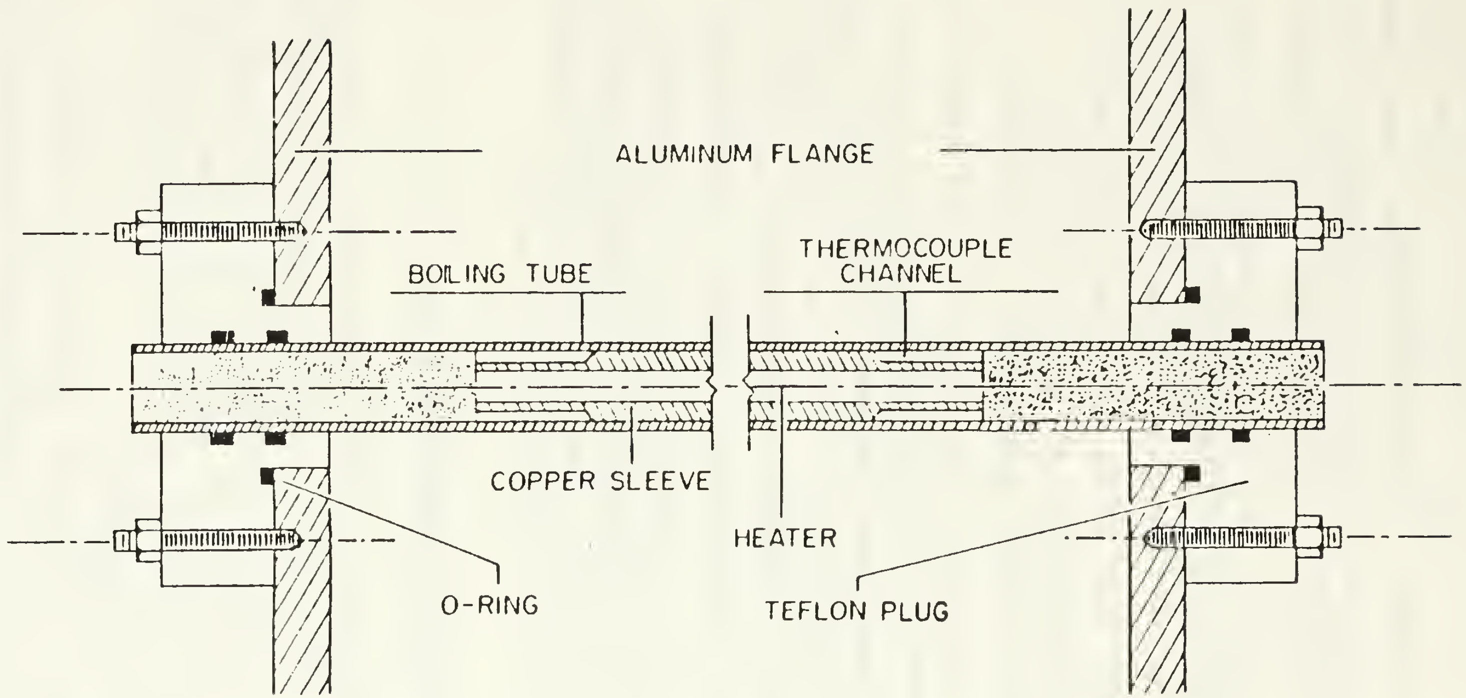


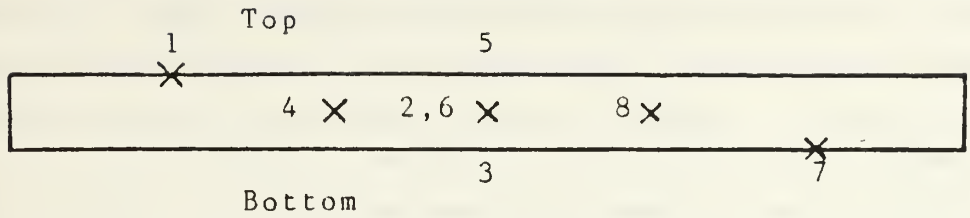
Figure 3.6 Sectional View of Long Boiling Tube.

eight 1.3 mm by 1.3 mm (0.050 in. by 0.050 in.) thermocouple channels in them. Figure 3.7 shows the details of the channel layout. The thermocouple hot junctions were welded to the sleeve. Appendix A describes the calibration of the thermocouples. The channels were oriented to provide both axial and circumferential readings of the tube inner wall temperature. The sleeve was soft soldered to the tube. The data on the short soft-soldered tube closely matched the reference solid-tube data, and the short soft-soldered-tube data matched similiarly with long tube data. The maximum circumferential wall temperature variation in the long smooth tubes was 0.80 K (0.31 °F) at 50 kW/m² compared to a solid tube circumferential variation of 0.34 K (0.61 °F). Section V.A describes in more detail the circumferential variation of temperature that resulted using the various tube construction methods. Some axial temperature variation was experienced in the long tubes, particularly the long High Flux tube. Non-uniform heat generation from the cartridge heater is believed to be responsible for the axial temperature variation. Section V.B descibes in more detail the long tube axial temperature variation.

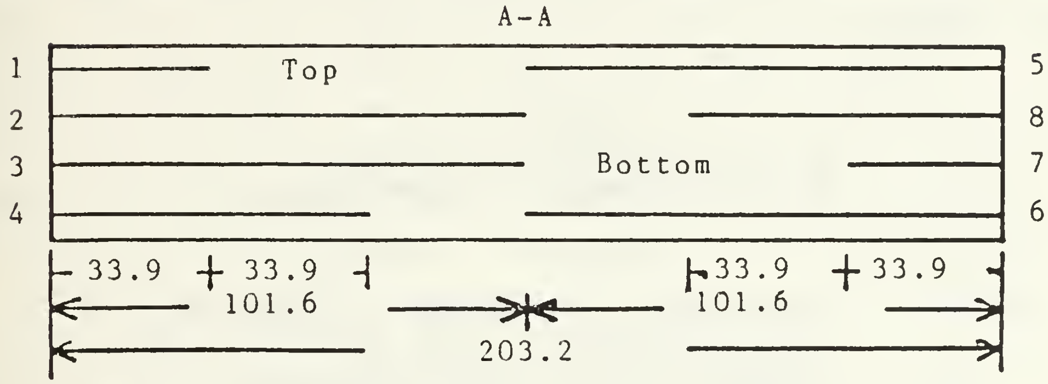
D. DATA ACQUISITION AND REDUCTION

A Hewlett-Packard 3497A automatic data acquistion/ control unit was used to read thermocouple outputs and to read an analog signal representing the current and voltage supplied to the cartridge heater. A Hewlett-Packard 9826A computer unit was used to control the HP-3497A and to analyze and store the data.

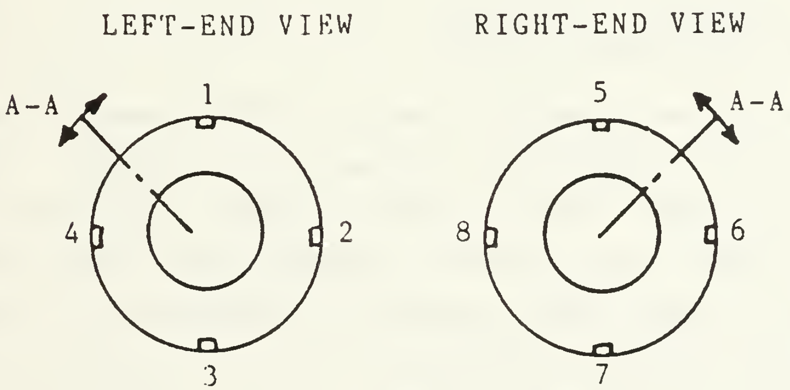
Information was entered through the computer keyboard to prompt the HP-3497A to automatically scan each channel. All thermocouple measurements were accomplished by 0.245 mm diameter (30 gage) copper-constantan (type-T) thermocouples.



(a) View of the boiling tube thermocouple locations as seen from the front of the experimental apparatus.



(b) Thermocouple sleeve unwrapped (at section A-A) to show the relative locations of the thermocouple channels (all dimensions in millimeters).



(c) End views of the boiling tube.

Figure 3.7 Long Tube Thermocouple Channels

A power sensing device, described by Karasabun [Ref. 8], converted the AC current and voltage values supplied to the cartridge heater to a 0-5 V analog, DC signal for scanning by the HP-3497A. Table 2 lists the channel allocations in the HP-3497A.

Following data acquisition for each point, results were computed according to the step-wise procedure outlined by Karasabun [Ref. 8], and summarized in Appendix B. Appendix B also includes a complete listing of the data-reduction program (DRP2).

TABLE 2

HP-3497A Channel Allocations

Channel	Purpose
25-32	Tube wall thermocouples (location T(1) to T(8) in long tube, T(5)-T(8) not used in short tubes)
33	Liquid R-114 thermocouple T(9)
34	Backup liquid R-114 thermocouple T(10)
35	R-114 vapor thermocouple T(11)
36	Sump thermocouple T(12)
62	Cartridge heater voltage analog signal
63	Cartridge heater current analog signal

E. COMPUTER-CONTROLLED VALVE

The computer-controlled valve (VC) was a Whitney, screwed bonnet, regulating valve with 3/8 in. Swagelok fittings. The valve travel was 10.5 turns from full shut to full open. The valve handle was replaced by a 101.6 mm (4 in.) hard rubber disk (seen in Figure 3.3) which was rotated by the motor pinion gear.

The computer-controlled motor was a General Electric "Minigear Motor" with a speed of 105.7 rpm and a torque of 3.39 N-m (30 lb-in). The motor direction was controlled by two sets of Crydom solid-state relays that acted to open,

shut, or hold the motor depending on signals from the computer. The computer controlled the amount of time that the valve was moving. Approximately 3 seconds were required for the motor to turn the valve one turn.

The flow through the valve was checked by a flow meter and verified to be approximately linear (1 turn = 10 percent flow) for the flows most often used. The valve position was tracked by a 10-turn potentiometer, which was connected to the computer-controlled motor by another 101.6 mm (4 in.) hard rubber disk driven off the motor pinion gear. Hard rubber disks were used instead of metal gears to avoid damage to the gear teeth during the program debugging stage. The rubber disks allowed sufficient slipping when, for example, the computer sent a valve-open signal even though the valve was fully open.

The R-114 liquid temperature input to the computer was provided by a separate copper-constantan thermocouple installed in the same liquid R-114 thermocouple well that the HP-3497A data acquistion/control unit used. The R-114 theromocouple emf for the computer was amplified by an Omega thermocouple DC millivolt amplifier before input in to the computer. The data acquisition system and the computer-controlled valve system were completely independent systems.

The computer used for the computer-controlled valve was an Octagon Systems SYS-2A microcomputer with an Esprit I terminal connected via an RS-232C serial port. Appendix C lists the control program used. The control program was written in NSC "Tiny BASIC." The control algorithm simulates a proportional-integral-derivative (PID) controller to vary the valve opening and shutting times. In the final program, limits were placed on the numerical value of certain program variables to prevent register overflow, jamming the valve fully open/shut, and to lessen the impact of system noise on the response of the system. NSC Tiny BASIC is limited to

integers from -32000 to 32000 and fractional numbers are truncated. The values of the weighting factors (A,B,C) for the proportional term (E), integral term (I), and derivative term (D) were determined by trial-and-error.

The control algorithm simplifies to the following lines:

```
 60 Input required temperature R
230 Read R-114 temperature M
260 Compute error (E), and change in error (D)
262 Add 1 each loop to integral sum (I) if error is positive
264 Add -1 each loop to integral sum (I) if error is negative
400 Valve command V=(E/A)+(B*D)+(I/C)
420 If (V>0) then open valve
430 Otherwise shut valve
540 GOTO 230
```

Section V.C desribes in detail the system response under this algorithm. Computer control of valve VC was not used during the data taking as originally planned. Section V.C discusses the reasons for this decision.

IV. EXPERIMENTAL PROCEDURES

A. INSTALLATION OF TUBE IN APPARATUS

Prior to installation in the apparatus, the boiling tube surface was cleaned with a 2 percent Nital solution (to remove surface oxidation and oil), rinsed with acetone, and air dryed. Short tubes tested with and without the above treatment showed no change in the heat-transfer perfcrmance. The treatment was effective in removing the slight surface oxidation present following soft soldering without changing the smooth or High Flux tube performance. Additionally, following testing with oil, a treatment was needed to return the High Flux surface to the "no-oil" condition for further testing.

After installing the tube in the glass tee, the apparatus was evacuated to 29 in. Hg by the portable mechanical vacuum pump (6) shown in Figure 3.1. System pressure was measured by a Marsh pressure gage (30 in. Hg to 150 psi range, ± 2.5 in. Hg and ± 0.5 psi accuracy). The apparatus was left at vacuum for 2 hours to check for leaks pricr to each run. No noticable drop in vacuum was observed within the accuracy of the pressure gage. Next, the system gage pressure was raised to 0.19 MPa (27 psi), the saturation pressure of R-114 at 21 ^{o}C (70 ^{o}F), by opening valve V7 (see Figure 3.1 for the configuration of the valves). An Automatic Halogen Leak Detector, TIF 5000, was used to check for R-114 leakage. The sensitivity of this detector is 3 ppm minimum concentration. After pressure equalization with the R-114 reservoir (3), the reservoir drain valve (V6) and condenser return valve (V5) were opened to fill the boiling tee with liquid R-114.

Prior to installation, the left end flange had been scribe marked to indicate the liquid level corresponding to 1600 cc (2500 gm) of liquid R-114 at 21 °C (70 °F). This was the mass of pure R-114 in the apparatus at the beginning of the data runs. The apparatus was now ready for taking data.

B. GENERAL OPERATION

Table 3 lists the 109 data runs accomplished during this thesis effort and their purpose. The data runs were numbered sequentially and preceeded by a 2- or 3-letter prefix to indicate the tube type. The tube prefixes were:

SS = Short Solid Tube
HF = High Flux Long Tube
WH = Wieland Hard Copper Long Smooth Tube
SSF = Short Slide-Fit Tube
SPF = Short Press-Fit Tube
SST = Short Soft-Soldered Tube
SHF = Short High Flux Tube

The short tube runs consisted of 6 data points at 6 different heat fluxes (usually 59, 37, 22, 14, 8, and 5 kW/m²). The normal tube runs consisted of at least 7 different heat fluxes with 6 data readings at each heat flux (usually 98, 61, 37, 22, 14, 8, and 5 kW/m²) with some additional low heat fluxes investigated for the 0, 3, and 10 percent oil cases to check for the onset of nucleate boiling and hysteresis in the High Flux surface.

In all cases, the data set was begun by starting the cooling pump (8) and opening valve VC slightly to slowly cool the liquid R-114 to the desired saturation temperature. The R-114 vapor temperature was also monitored and when both liquid and vapor temperatures were stable (usually after 30-45 minutes), the heat flux would be established, the saturation temperature reestablished, and the data aquisition unit was allowed to take data. Usually, the vapor

TABLE 3

Summary of Data Runs

Run No.	Tsat (°C)	No. Pts	Remarks
WH10			Runs WH01 to WH10 taken by Karasabun
SPF11	6.7	3	Debug new tube
SPF12	-2.2	6	Press-fit tube 4 (0.004 in. interference)
SPF13	2.2	6	Effect of Tsat
SPF14	6.7	6	Effect of Tsat
SSF15	-2.2	6	Slide-fit tube 2 (0.005 in. clearance)
SSF16	2.2	6	Effect of Tsat
SSF17	6.7	6	Effect of Tsat
SSF18	-2.2	6	Rotate tube 90 degrees
SSF19	-2.2	6	Study low heat flux error band
SSF20	-2.2	6	Study high heat flux error band
SSF21	-2.2	6	Rotate heater -90 degrees, tube fixed
SSF22	6.7	6	Shift heater and thermocouples
SSF23	-2.2	6	Repeatability
SPF24	-2.2	6	Repeatability
SPF25	-2.2	6	Repeatability
SPF26	-2.2	6	Shift heater and thermocouples
SPF27	-2.2	6	Clean with Nital, acetone, and air dry
SPF28	6.7	6	Repeatability
SSF29	-2.2	6	Slide-fit tube 3 (0.002 in. clearance)
SSF30	6.7	6	Effect of Tsat
SPF31	-2.2	6	Repeatability
SPF32	-2.2	6	Time Variation Study (1 day later)
SPF33	2.2	6	Effect of Tsat
SPF34	6.7	6	Effect of Tsat
SS35	-2.2	6	Short Solid Tube
SS36	-2.2	6	Repeatability
SS37	6.7	6	Effect of Tsat
SPF38	-2.2	6	4 days later
SPF39	-2.2	6	Shift heater and thermocouples
SPF40	-2.2	6	7 days later
SPF41	-2.2	6	10 days later
SS42	-2.2	6	Time Study Solid Tube (no effect)
SST43	-2.2	6	Short soft-soldered tube 6
SST44	-2.2	6	Repeatability
SHF45	-2.2	4	Debug short High Flux tube 7
SHF46	-2.2	5	Study Tvapor superheat
SHF47	-2.2	7	Repeatability
SHF48	-2.2	8	Repeatability
SHF49	-2.2	6	Study hydostatic head (+1 in. level)
SHF50	-2.2	6	-Increase data pts at heat fluxes
SHF51	-2.2	6	-Runs 49-54 form data set
SHF52	-2.2	6	-Each run at different heat flux
SHF53	-2.2	6	-Compare with set 55-60
SHF54	-2.2	6	End of Set 49-54
SHF55	-2.2	6	Study hydrostatic head (+0.5 in. level)
SHF56	-2.2	6	-same as above set 49-54
SHF57	-2.2	6	-same
SHF58	-2.2	6	-same
SHF59	-2.2	6	-same
SHF60	-2.2	6	End of Set 55-60
SHF61	-2.2	6	Install Tvapor radiation shield
SHF62	-2.2	6	Study Tliquid subcooling
SHF63	-2.2	6	Clean High Flux w/Nital and acetone
SHF64	-2.2	6	Repeatability
SHF65	-2.2	6	Repeatability
SHF66	-2.2	6	Repeatability
SHF67	-2.2	7	Rotate tube +90 and +180 degrees
SHF68	-2.2	6	Repeatability

Table 3

Summary of Data Runs (cont'd)

Run No.	Tsat (°C)	No. Pts	Remarks
SHF69	-2.2	7	Apply thermal grease to heater (no effect)
SHF70	6.7	36	Effect of Tsat
SHF71	-2.2	36	Repeatability
SHF72	-2.2	36	Debug oil addition (0.2 percent added)
SHF73	-2.2	36	Remove and clean tube, add 1 percent oil
SHF74	-2.2	36	2 percent oil
SHF75	-2.2	36	3 percent oil
SHF76	-2.2	36	6 percent oil
SHF77	-2.2	36	10 percent oil
WH78	-2.2	9	Axial/Circumferential variation study
WH79	-2.2	42	0 percent oil, decreasing q
WH80	-2.2	11	Rotated tube -90 and -180 degrees
WH81	-2.2	42	Repeatability (of run WH79)
WH82	-2.2	42	0 percent oil, increasing q
WH83	-2.2	38	Repeatability (of run WH82)
WH84	6.7	49	0 percent oil, increasing q
WH85	-2.2	66	0 percent oil, decreasing q
WH86	-2.2	48	1 percent oil, decreasing q
WH87	6.7	48	1 percent oil, decreasing q
WH88	-2.2	48	2 percent oil, decreasing q
WH89	6.7	48	2 percent oil, decreasing q
WH90	-2.2	36	3 percent oil, increasing q
WH91	-2.2	48	3 percent oil, decreasing q
WH92	6.7	48	3 percent oil, decreasing q
WH93	6.7	48	6 percent oil, decreasing q
WH94	-2.2	48	6 percent oil, decreasing q
WH95	-2.2	61	10 percent oil, increasing q
WH96	6.7	53	10 percent oil, increasing q
WH97	-2.2	66	10 percent oil, decreasing q
WH98	-2.2	45	Repeatability (of run WH95)
WH99	6.7	66	10 percent oil, decreasing q
HF100	-2.2	66	0 percent oil, increasing q
HF101	-2.2	72	0 percent oil, decreasing q
HF102	-2.2	24	Repeatability (of run HF100)
HF103	6.7	66	0 percent oil, increasing q
HF104	6.7	69	0 percent oil, decreasing q
HF105	6.7	56	Repeatability (of run HF104)
HF106	-2.2	48	1 percent oil, decreasing q
HF107	6.7	48	1 percent oil, decreasing q
HF108	6.7	48	2 percent oil, decreasing q
HF109	-2.2	48	2 percent oil, decreasing q
HF110	6.7	48	3 percent oil, decreasing q
HF111	-2.2	39	3 percent oil, increasing q
HF112	-2.2	72	3 percent oil, decreasing q
HF113	-2.2	48	6 percent oil, decreasing q
HF114	6.6	48	6 percent oil, decreasing q
HF115	-2.2	48	10 percent oil, increasing q
HF116	-2.2	72	10 percent oil, decreasing q
HF117	6.7	72	10 percent oil, decreasing q
HF118	6.7	48	10 percent oil, increasing q
SPF119	-2.2	36	Complete study of time variation SPF

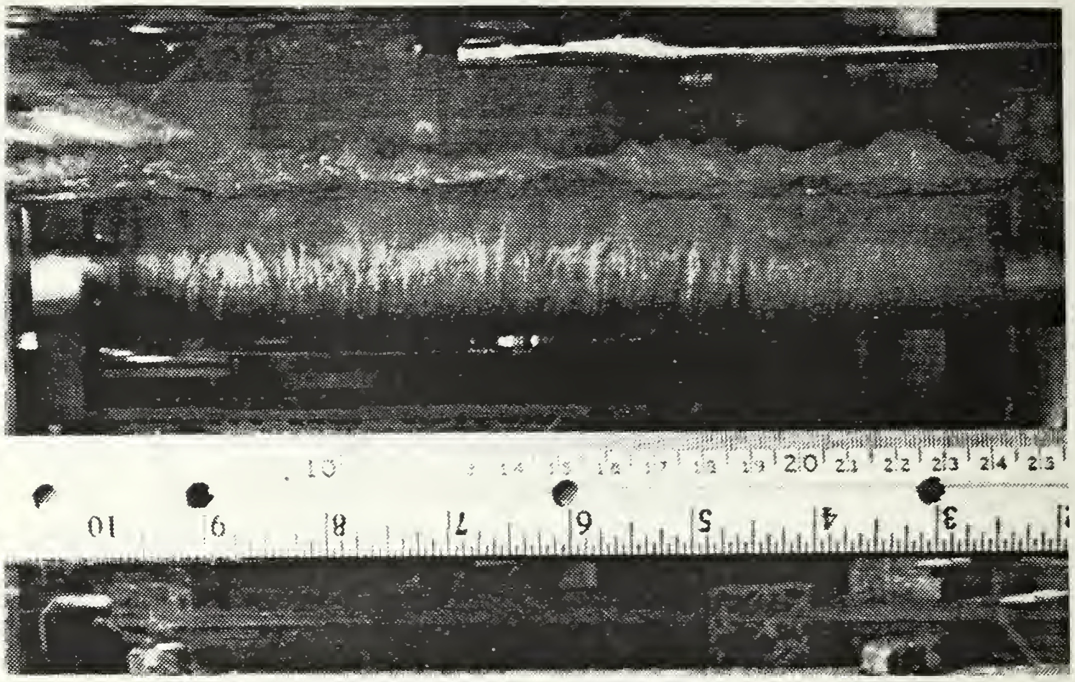
Note: 75 data runs for Computer-Controlled Valve testing not listed.

temperature would read higher, up to 2 K, than the liquid temperature due to the vapor becoming superheated. The apparatus, though cocled by the R-114, was still hot enough (60 °F) to superheat the vapor. Measurements of the liquid temperature, system pressure, and vapor temperature (with vapor probe shielded by a radiation shield) confirmed this. The liquid temperature best indicated the saturation temperature.

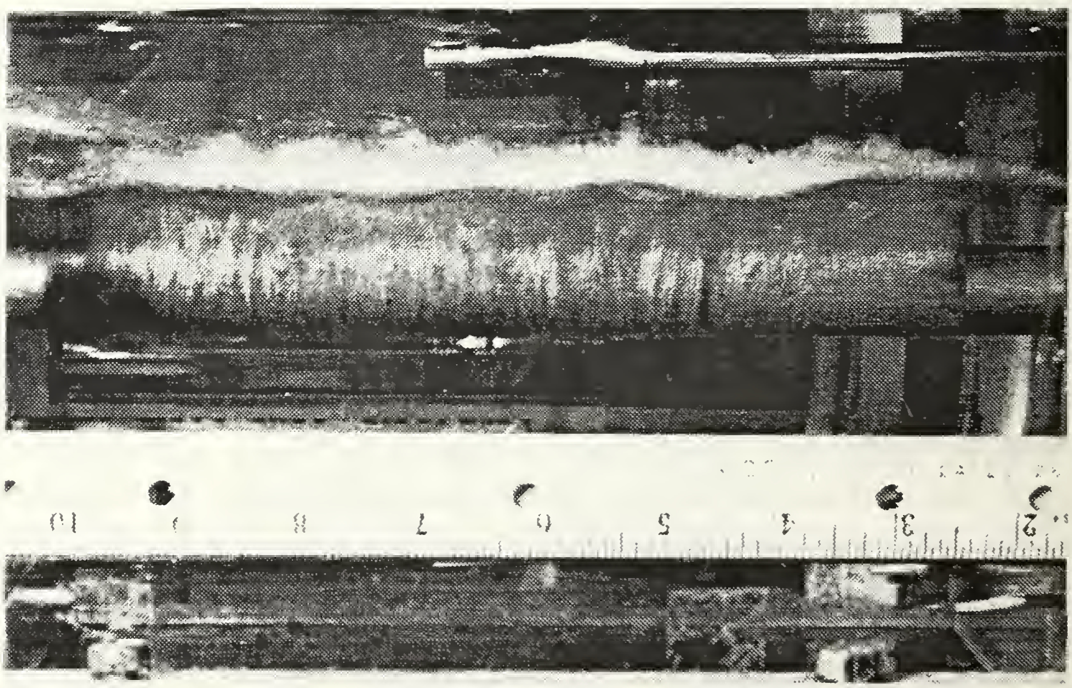
The HP-3497A data aquisition unit would scan each channel, compute the heat-transfer coefficient, print the results (an example printout is shown in Appendix D), and store the data on the floppy disk.

Following the taking of all data points, the data set was statistically analyzed by subroutine STATS to compute the average heat-transfer coefficient at each heat flux and the standard deviation of the 6 data points for a given heat flux. The standard deviation of the 6 data points was usually 0.5 percent for the heat flux and 1-2 percent for the heat-transfer coefficient.

After all data sets at a given oil concentration were complete, oil was added via valve V1. The oil immediately dissolved in the R-114. No carryover to the condenser was noted except for several small drops at 10 percent oil and the highest heat flux during the last few data sets. Foaming occurred with the addition of oil, and increased with both increasing heat flux and increasing oil concentration. Figure 4.1 to 4.3 show photographs at heat fluxes of 30 kW/m² and 98 kW/m² for oil concentrations of 0, 3, and 10 percent. When oil addition was not taking place, the oil cylinder and reservoir were isolated from the apparatus by valves V3 and V4 to minimize R-114 absorption by the oil.

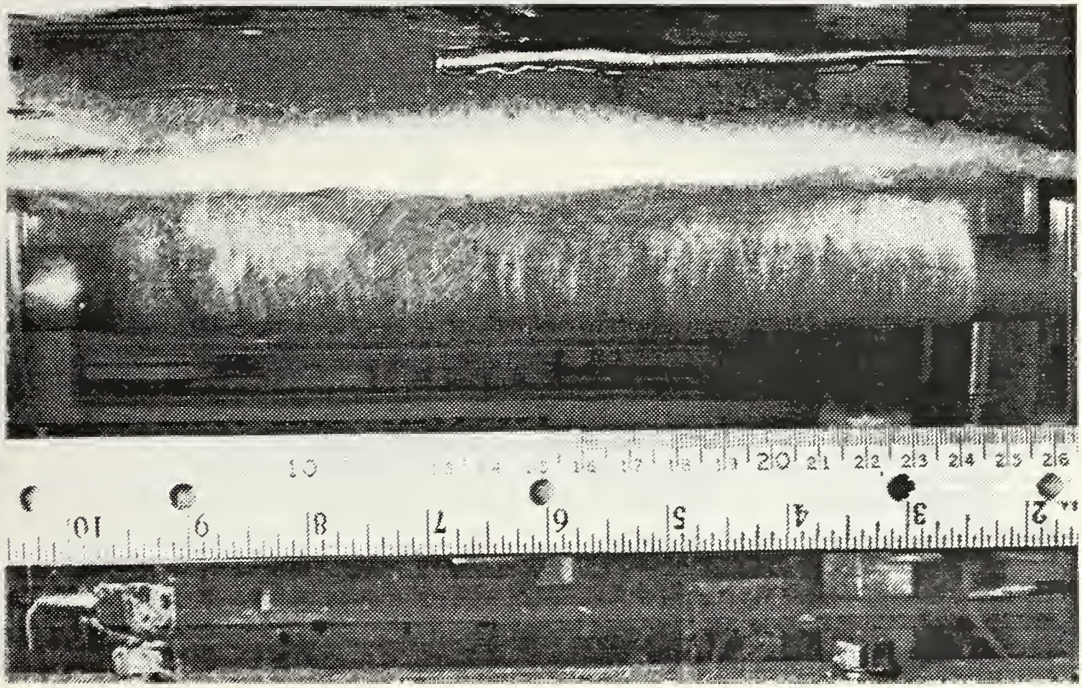


(a) 0 percent oil at 100 kW/m^2. No Foaming.

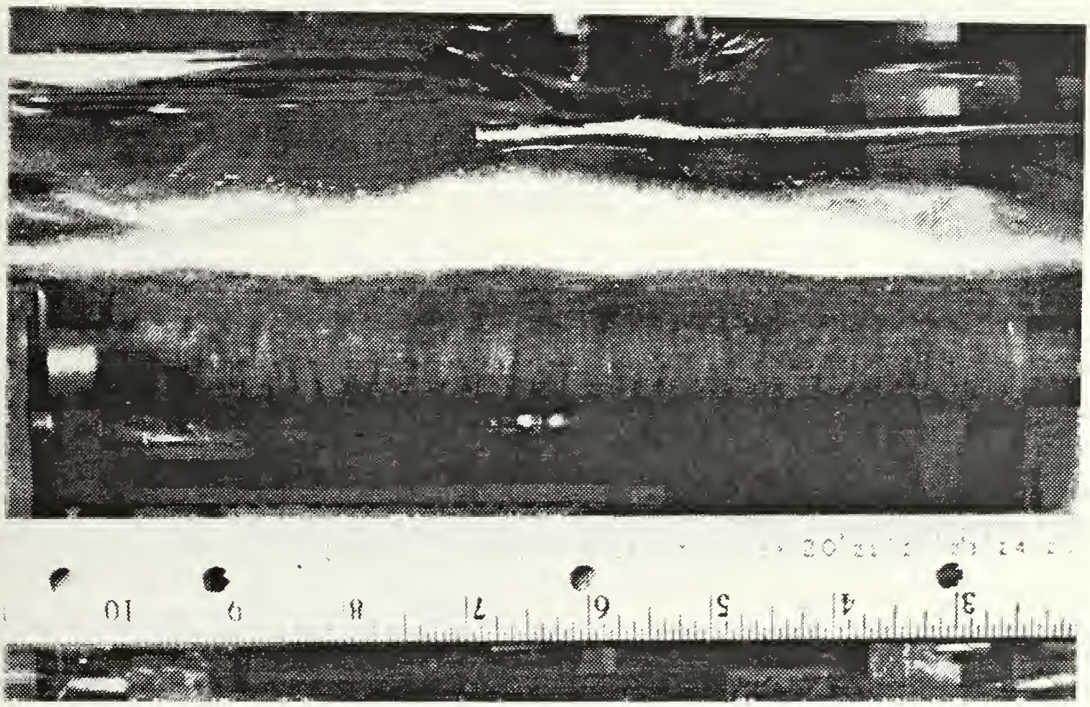


(b) 1 percent oil at 100 kW/m^2. Foaming begins to appear.

Figure 4.1 Photographs of Boiling and Foaming at 0 and 1 Percent Oil.



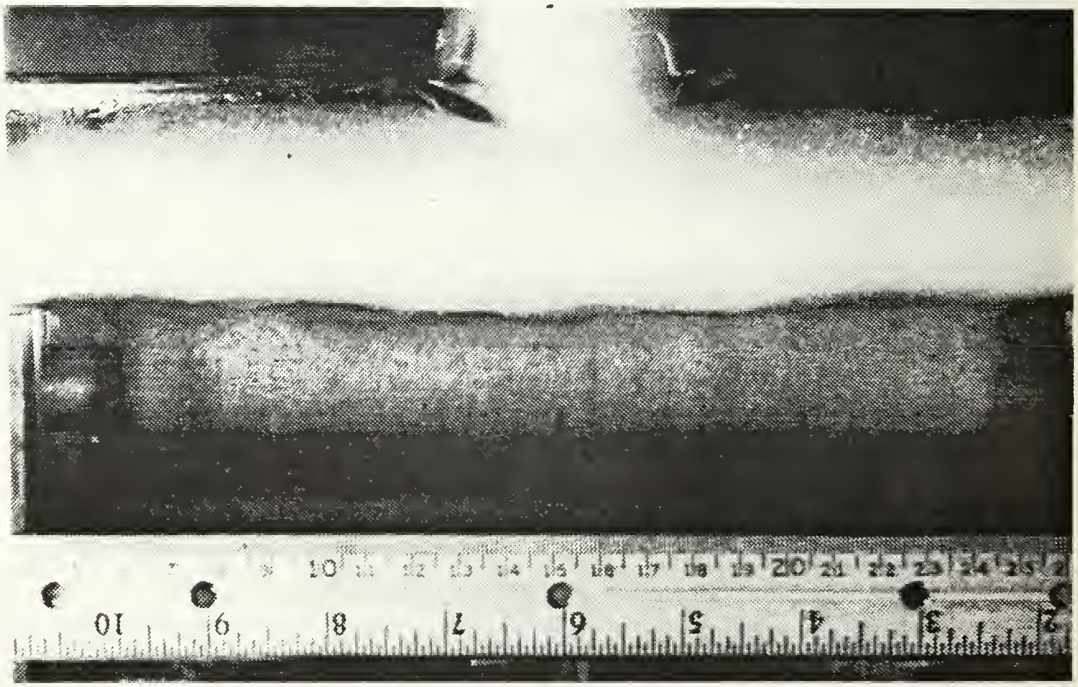
(a) 3 percent oil at 37 kW/m^2.



(b) 3 percent oil at 100 kW/m^2.

Figure 4.2 Photographs of Boiling and Foaming at 3 Percent Oil.

(a) 10 percent oil at 37 kW/m^2.



(b) 10 percent oil at 100 kW/m^2.

Figure 4.3 Photographs of Boiling and Foaming at 10 Percent Oil.

C. SAMPLING OIL

Oil sampling was done at room temperature to prevent the temperature of the sampling lines from boiling off the R-114 and yielding false readings. The sampling procedure used was:

1. Weigh the empty flexible sample tubing and pinch clamps. Connect them to the sampling apparatus.
2. Open S-1, S-4, and set S-2 to position 2 to provide a purge path for the sample flow.
3. Lower the sample container to a height below the level of the R-114 glass tee.
4. After purging the sample probe and lines, use pinch clamps to isolate the 304.8 mm (12 in.) flexible sample tubing and trap a sample. Shut S-1 and switch S-2 to position 1.
5. Disconnect the flexible sample tubing and immerse it in ice to lower its internal pressure below atmospheric pressure.
6. Open S-3 to provide a vent for the purge container and pour the purge volume back into the boiling tee by lifting it to a height so that it flows by gravity.
7. Weigh the sample line (the mass balance used was accurate to ± 0.0001 g).
8. Open a pinch clamp and allow air to warm the sample line and evaporate off the liquid R-114. Keep the sample line on the mass balance to collect any drops of oil that may splatter as the liquid R-114 evaporates.
9. After allowing several hours for the R-114 to evaporate, reweigh the flexible sample tubing.
10. Calculate the mass percent of oil using equation (3.1).

V. SYSTEM OPERATION AND PROBLEMS

A. CIRCUMFERENTIAL WALL TEMPERATURE VARIATION

Following the construction of the solid, thick-walled, reference tube, an investigation was begun to develop an assembly method which would result in negligible contact resistance between the inner tube wall and the copper sleeve, and yield data comparable to that for the solid tube.

Short slide-fit tubes 2 and 3 (see Table 1) had sleeves that could be slid into the test tube with tube 3 having a tighter clearance. The slide-fit tubes exhibited a circumferential wall temperature variation of 7-14 K at 50 kW/m² in pure R-114 boiling at -2.2 °C. This variation matched data on a similar long tube (with slide-fit sleeve) tested by Karasabun [Ref. 8]. Tube 2 had an average wall temperature of 33 °C and tube 3 had an average wall temperature of 25 °C at 50 kW/m². The tighter clearance of tube 3 resulted in a lower contact resistance, and the wall temperature subsequently dropped. The short solid tube under similar conditions exhibited a 0.34 K circumferential wall temperature variation and an average wall temperature of only 10.7 °C. Sauer et al. [Ref. 21], with a similar experimental apparatus, used a mechanically-press-fitted brass sleeve for obtaining data. Tubes 4 and 5 had copper sleeves that were mechanically cold pressed into the tube. The diametral interference was 0.01 mm (0.0004 in.) for tube 4 and 0.015 mm (0.0006 in.) for tube 5. The interface pressure obtained was calculated to be 15.2 MPa (2200 psi) for tube 4 and 22.8 MPa (3300 psi) for tube 5. During pressing, the sleeves were lubricated with glycerin ($C_3H_8O_3$) a

high-thermal-conductivity compound that, according to Incropera and Dewitt [Ref. 22], should result in a 10-100 times reduction in the contact resistance when combined with the contact pressures mentioned above.

Tubes 4 and 5 had circumferential wall temperature variations of 0.9-1.5 K with an average wall temperature of 16.2 °C for tube 4 and 14.7 °C for tube 5 during initial testing. However, with time, the circumferential wall temperature variation grew to 5-8 K and the average wall temperature increased to about 28 °C for both tubes. The resulting drop in heat-transfer performance is shown in Figure 5.1. This result is believed to be due to the phenomenon referred to as "stress relaxation."

Stress relaxation is a form of creep. The Metals Handbook [Ref. 23] notes that copper alloys easily undergo a decrease in stress resulting from transformation of elastic strain into plastic strain in a constrained solid. The phenomena occurs even at relatively low operating temperatures (at 25 °C, an 80 percent drop in stress can occur in 200 hours), and is of most concern in applications like press-fits and solderless wrapped copper connectors. The time-dependent data of Figure 5.1 appears to be the result of a dropping press-fit interface pressure yielding a higher contact resistance, higher inner wall temperatures, and lower heat-transfer coefficients.

Stephan and Mitrovic [Ref. 7] used a combination of mechanically press-fit and soft-soldered inner sleeves to obtain data on the Gewa-T surface in R-114. Soft-soldering was initially overlooked by this experimenter because the normal heating method used is an oxy-acetylene torch on the tube surface. The flame temperatures of an oxy-acetylene torch are above 800 °C (1500 °F). The resulting oxidation and heat damage (the High Flux coating melts at 800 °C) to the High Flux surface was unacceptable. Tests showed

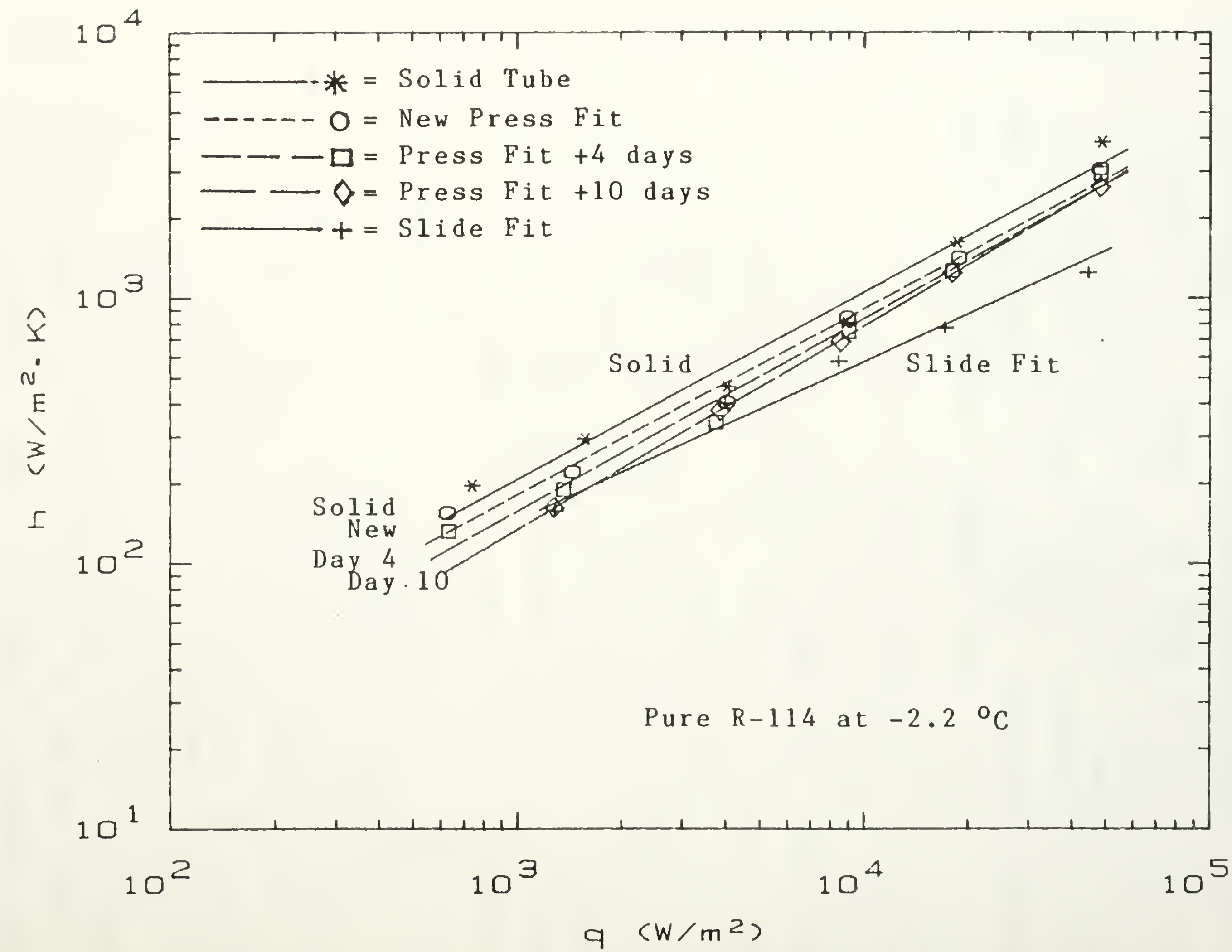


Figure 5.1 Time Dependency of the Measured Heat-Transfer Coefficient in Press-Fit Tubes.

however, that the inner cartridge heater could be used to apply a controlled amcunt of heat to melt a low temperature (melting point 160 °C) solder, while closely monitoring the tube temperature using the sleeve thermocouples. This method was used to produce soft-soldered short tube 6 which showed circumferential wall temperature variations of 0.8 K and an average wall temperature of 11.5 °C at 50 kW/m². Figure 5.2 compares the results of the soft-soldered and solid tubes. The agreement between the tubes is excellent. The long boiling tubes matched the short soft-soldered data very closely.

Tests made by rotating the test tubes 90 degrees and 180 degrees showed that the slight circumferential wall temperature variation of these tubes was due to the surface characteristics of the boiling tube rather than due to the thermocouples. Thermocouples located near more active nucleation sites of the smooth and High Flux surfaces had slightly lower local wall temperatures. The 0.8 K circumferential wall temperature variation that resulted from soft-soldering the sleeves of the tubes is much smaller than the 11 K variation reported by Sauer et al. [Ref. 21], and is about the same as the 1 K variation reported by Stephan and Mitrovic [Ref. 7].

B. AXIAL TEMPERATURE VARIATION OF LONG TUBES

Karasabun [Ref. 8] reported an axial temperature variation of about 20 K along the inner wall of his slide-fitted sleeve. Stephan and Mitrovic [Ref. 7] reported an axial temperature variation of 1 K along the sleeve they used. The long soft-soldered tubes tested in this experiment exhibited an axial temperature distribution that varied with heat flux. Figures 5.3 and 5.4 show the axial temperature distribution as a function of position along the boiling

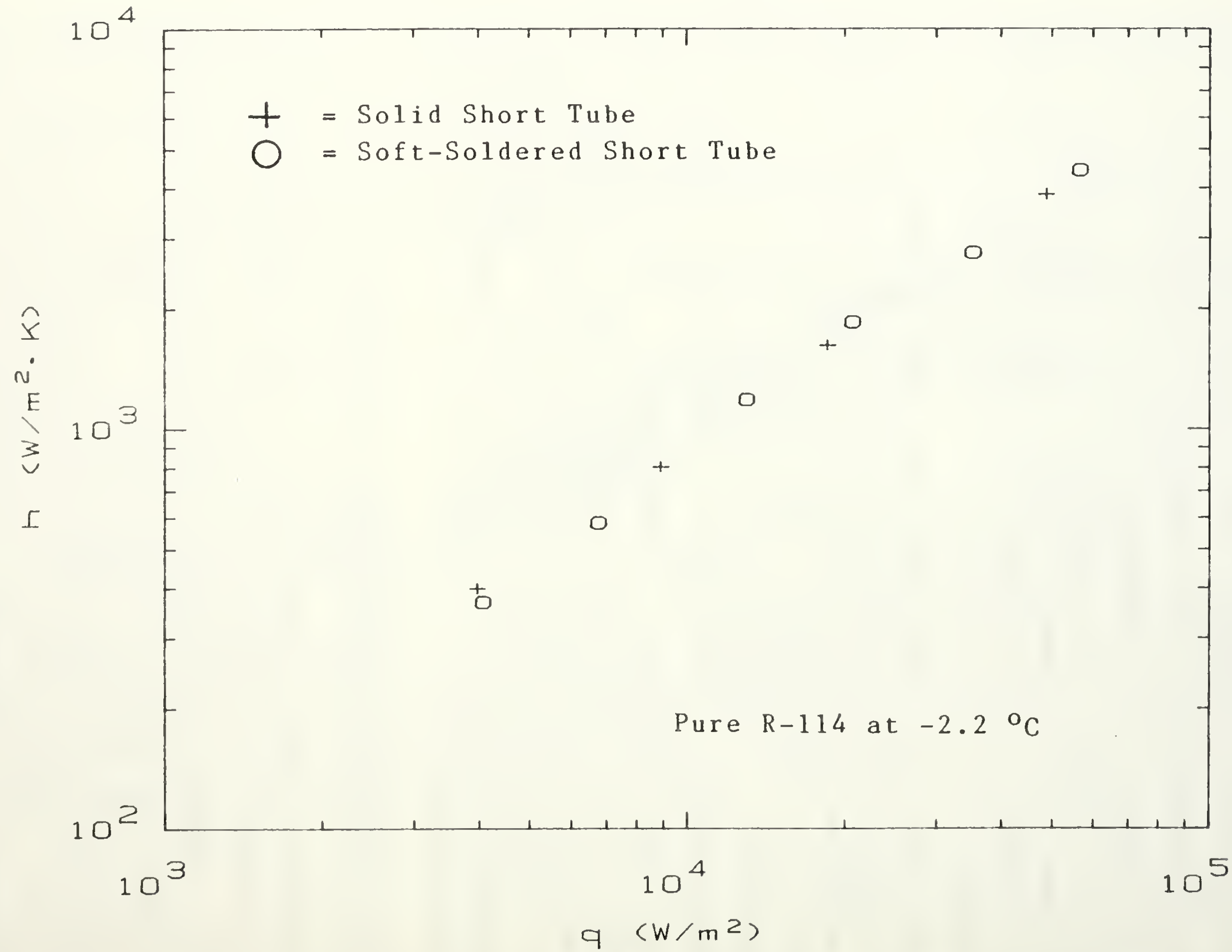


Figure 5.2 Comparison of Solid and Soft-Soldered Short Tube Heat-Transfer Coefficients.

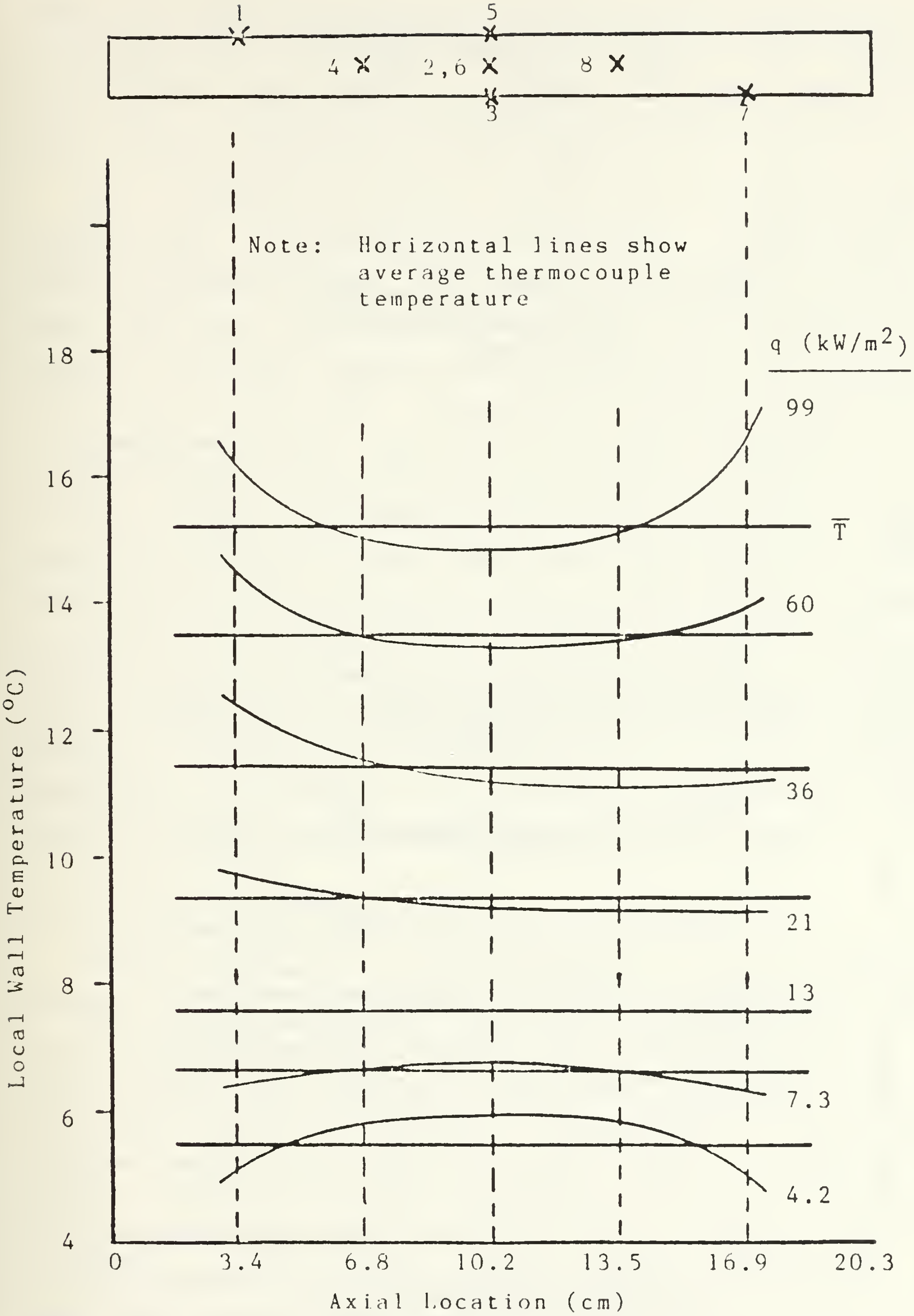


Figure 5.3 Axial Temperature Variation of Smooth Tube.

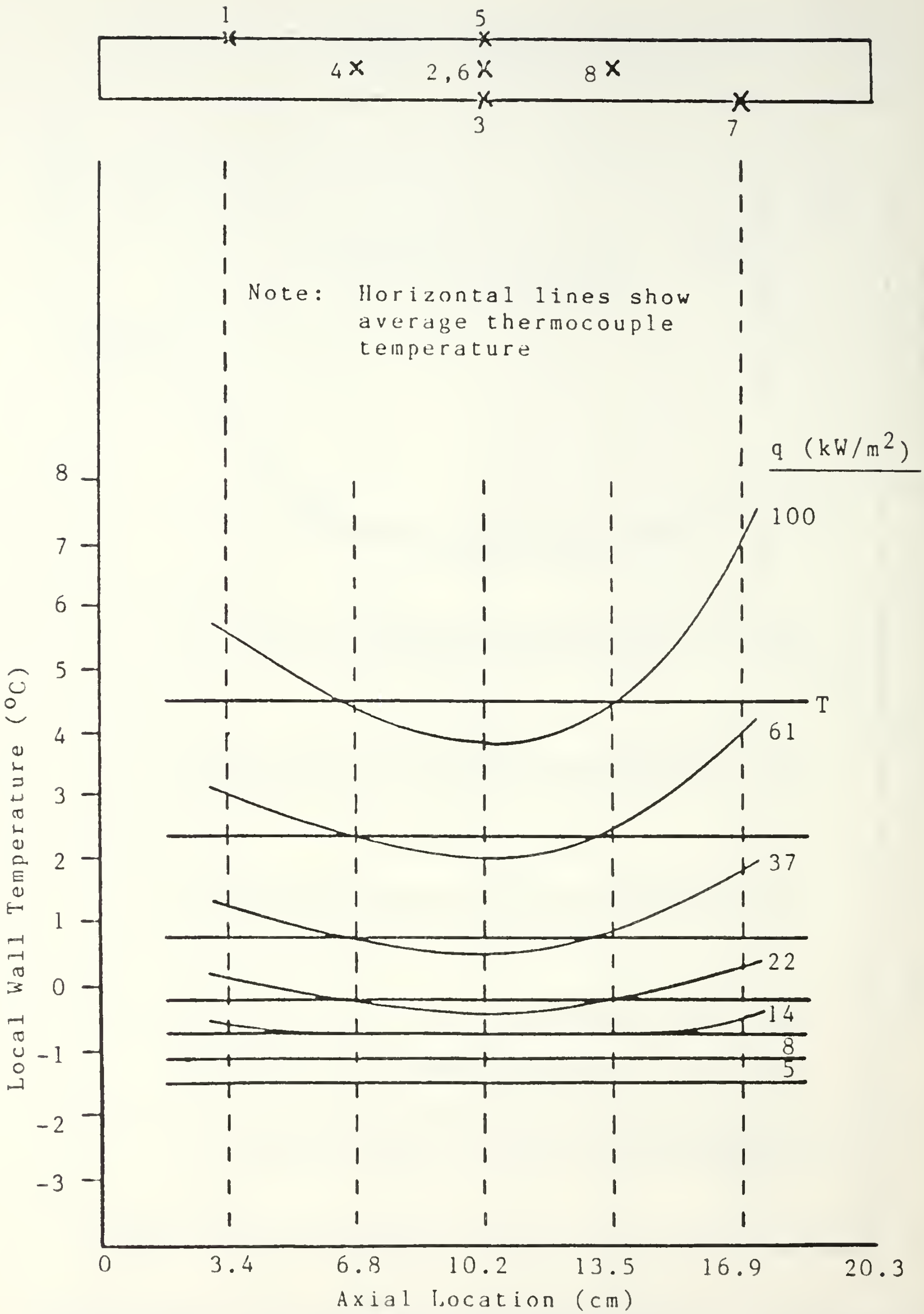


Figure 5.4 Axial Temperature Variation of High Flux Tube.

surface for the smooth tube and High Flux tube respectively. The variation at 20 kW/m^2 (the heat flux at which Stephan and Mitrovic cite their 1 K variation) is less than 1 K for both tubes. The maximum axial temperature variation is 3 K for the High Flux surface at 98 kW/m^2.

The cartridge heaters used were precision-wound, ceramic-core, magnesium-oxide-insulated, Incoloy-sheathed WATLOW FIREROD heaters. The heaters had 6.35 mm (0.25 in.) long lava-rock plugs at either end of the heater that reduced the actual heating length on each end. The heaters were initially believed to generate a uniform heat flux at all power settings, but the axial wall temperature data indicate the heat generation varied with the power level.

Since the axial temperature distribution was fairly linear over most practical heat fluxes (less than 37 kW/m^2), the arithmetic average of all 8 wall thermocouples was used to compute the heat-transfer coefficient. This results in slightly lower heat-transfer coefficients and is a conservative estimate of the performance of the High Flux surface. Appendix E analyzes the resulting error in the heat-transfer coefficient from using the arithmetic average for calculating the heat-transfer coefficient.

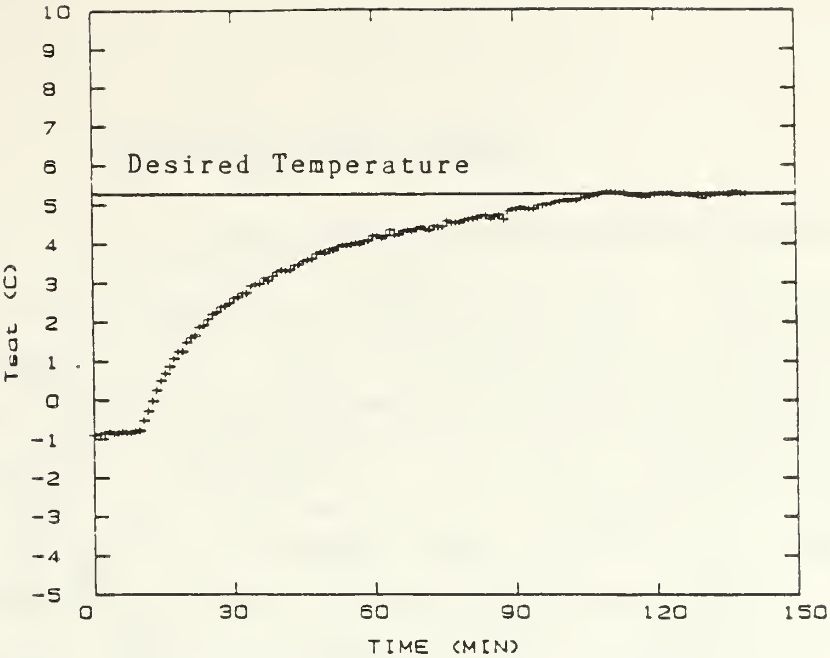
C. COMPUTER-CONTROLLED VALVE

Figure 5.5 shows the system response to closing valve VC manually and the improved response of the system when using the computer-controlled valve. By correctly cycling the valve between open and shut, the system saturation temperature could rapidly be changed. Establishing a stable equilibrium temperature after a large valve movement was, however, difficult during the initial testing of the apparatus. The extensive trial-and-error testing for the correct weighting factors of the proportional, integral, and

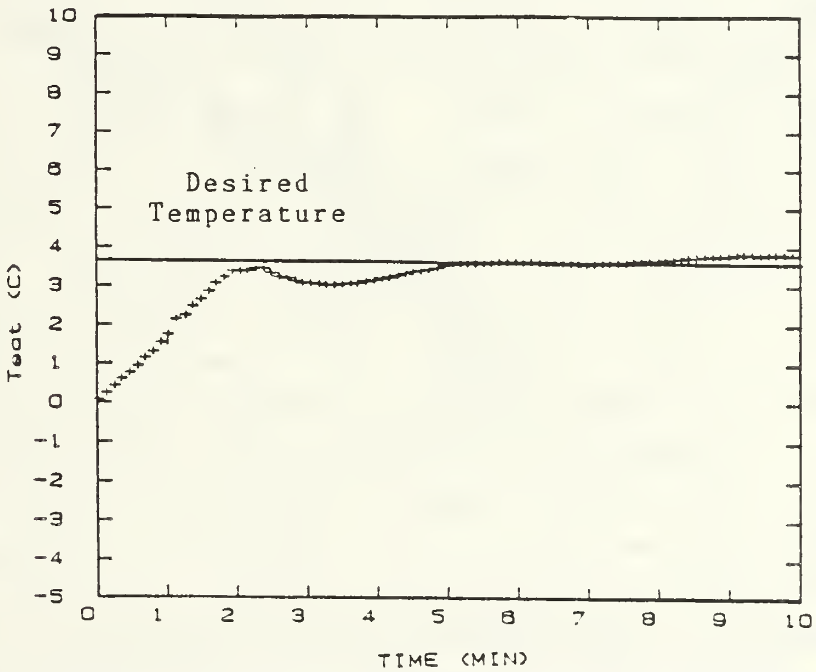
derivative terms resulted in a large data base concerning the saturated system operating characteristics and a large amount of practice for the operator in manual control of valve VC following unsuccessful computer-controlled transients.

Manual operation of valve VC was done in conjunction with the section of the data-reduction program (lines 1890 to 2485 of program DRP2 listed in Appendix B) that monitored the saturation temperature and the rate of change of saturation temperature continuously. It was found that, because of the better temperature resolution of the HP-3497A data acquisition unit, with manual operation and a trained operator, temperature transients could be maintained within ± 0.02 K. This was a much tighter control band than was possible with the computer-controlled valve because of the poor resolution of its temperature sensing input from the Omega thermocouple DC millivolt amplifier. Additionally, after much practice and experience, the manual method was found to be as fast as, or faster than the use of computer-controlled valve.

To obtain the highest accuracy data in the shortest period of time, computer-control of valve VC was abandoned. Section VII.B includes recommendations for further improvements to the computer control system to restore its usefulness.



(a) Natural system response to shutting valve VC to cause a desired increase in system temperature.



(b) Improvement in system response time using computer control of valve VC to reach a desired temperature (note the different time scale).

Figure 5.5 System Response to a Transient with Computer-Controlled Valve.

VI. RESULTS AND DISCUSSION

A. BOILING PERFORMANCE OF SMOOTH TUBE

Figure 6.1 shows the nucleate pool-boiling performance of the smooth copper tube in R-114. The behavior with no oil represents typical nucleate pool-boiling performance. From point A to point B, a continuous increase in wall superheat ($\bar{T}_{wo}-T_{sat}$) is observed when heat flux is increased. No bubbles were observed in this region of the curve as this region represents natural convection. At point B, incipient nucleate boiling occurs. From point B to point C (or C' for 10 percent oil), a reduction in wall superheat is observed while the heat flux is continuously increased. This region is known as the mixed-boiling region, where transition from natural convection to nucleate pool boiling takes place. In this region, the heated portion of the tube began to activate an increasing number of nucleation sites, while the unheated ends showed no bubbles. In fact, the unheated ends underwent only natural convection, due to axial conduction of heat along the tube wall, at all heat fluxes. The transition from natural convection to nucleate boiling occurred rapidly when there was no oil present. The surface would burst into nucleate boiling in less than a second after the first nucleation site became active. At point C (or C'), all the available nucleation sites were apparently active. After point C, the wall superheat again increases with increasing heat flux as shown in region C-D. In region C-D, no new nucleation sites were seen to become active. Instead, the bubble departure rate increased. When the heat flux is decreased after having established complete nucleate boiling, the curve follows a

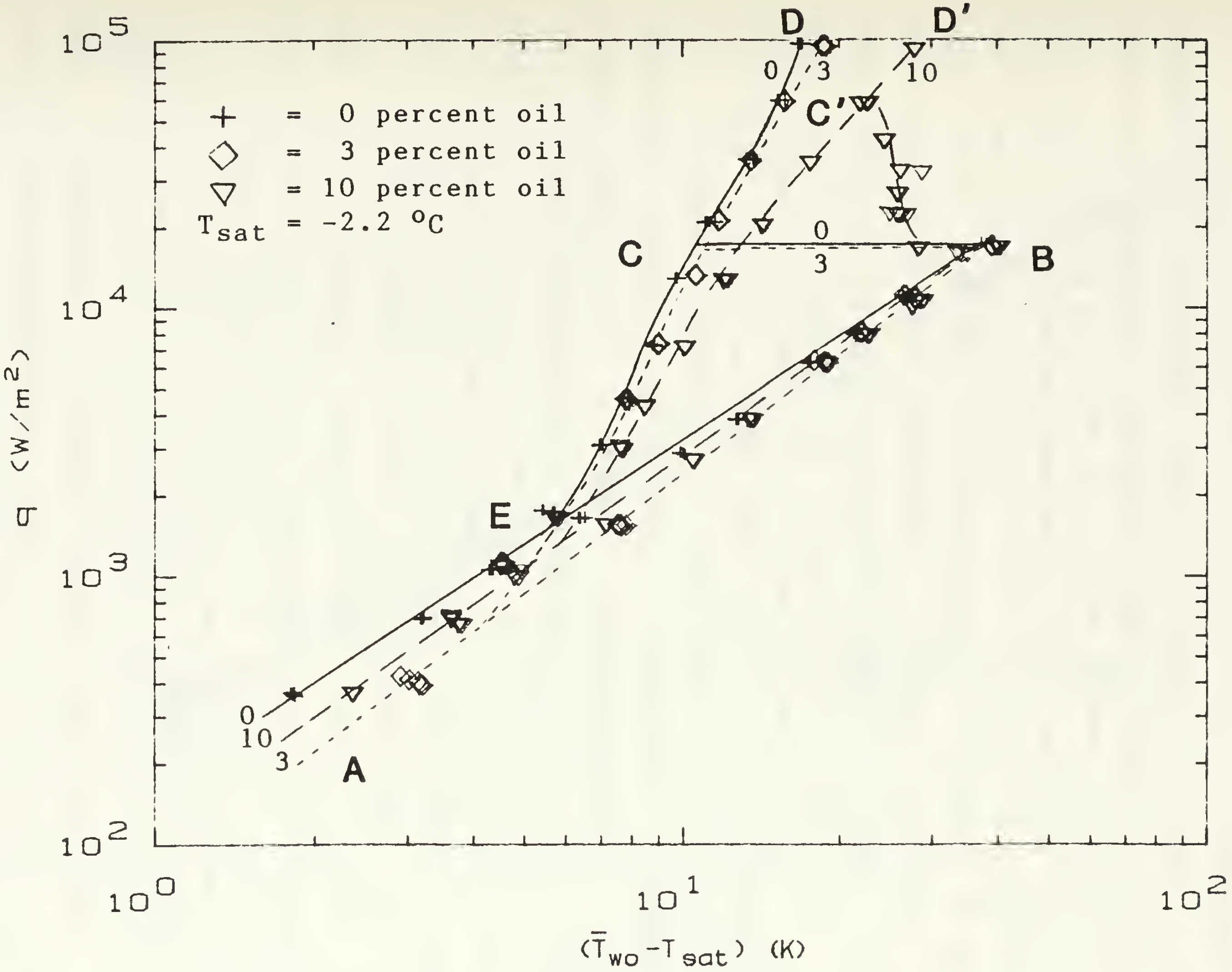


Figure 6.1 Heat-Transfer Performance of Smooth Tube.

different path (point D to point E). The existence of stable nucleation sites, which remain active over a wide range of heat fluxes, results in better heat-transfer performance than in natural convection, resulting in a lower wall superheat.

The effect of adding oil is, according to Stephan [Ref. 9], to introduce a mass diffusion resistance and lower the heat-transfer coefficient. As seen in Figure 6.1, in region A-B, both the 3 and 10 percent curves were lower than the 0 percent oil curve. The 3 percent oil curve is lower than the 10 percent oil curve probably because of the non-linear physical property variations of refrigerant-oil mixtures. The non-linear variation of surface tension (see Figure 2.3) would not seem to be responsible for this anomally. The curves in region A-B support the contentions of Chongrungeong and Sauer [Ref. 10] and Thome [Ref. 14] that the non-linear variation of physical properties of refrigerant-oil mixtures, other than surface tension, explains the heat-transfer behavior of refrigerant-oil mixtures. The effect of adding 10 percent oil was to delay the transition to complete nucleate boiling on the tube. With 10 percent oil, the surface developed patches of nucleation sites that spread slowly with increasing heat flux, until they covered the entire surface (point C'). Region D-E (or D'-E) shows that oil increased the wall superheat slightly for 3 percent oil and significantly for 10 percent oil. Again, this agrees with the concept of an increased mass diffusion resistance by the addition of oil.

Figure 6.2 shows the heat-transfer coefficient of the smooth tube in R-114-oil mixtures as a function of heat flux. The curves show the heat-transfer coefficient of the smooth tube in region D-E, after complete nucleate boiling has been initiated. The effect of adding less than 6 percent oil is seen to be small (about a 10 percent

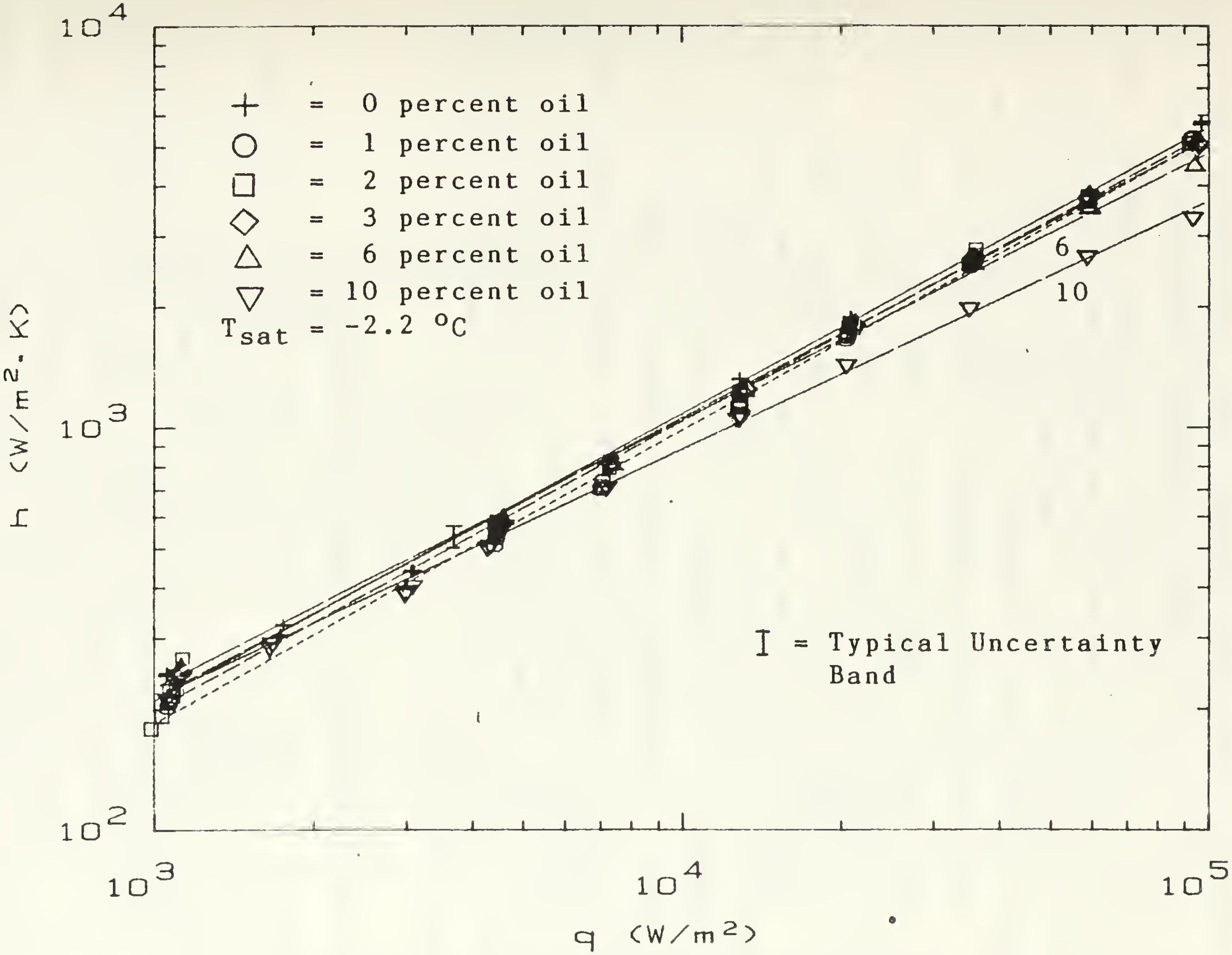


Figure 6.2 Boiling Heat-Transfer Coefficient of Smooth Tube.

reduction in the heat-transfer coefficient). However, an oil concentration of 10 percent causes a more significant drop in the heat-transfer coefficient (from 0 to 35 percent depending on the heat flux).

Figure 6.3 shows more easily the degradation that oil causes in the boiling heat-transfer performance of the smooth tube. This figure plots the heat-transfer coefficient of the smooth tube relative to the heat-transfer coefficient in pure R-114 as a function of oil concentration. The effect of oil can be seen to depend also on the heat flux. Oil can be seen to generally degrade the performance of the smooth tube, except at heat fluxes less than 5 kW/m^2 and oil concentrations between 2 and 8 percent. This behavior was also seen by Henrici and Hesse (see Figure 2.2). Since this curve shows the heat-transfer performance in region D-E, with complete nucleate boiling, the non-linear variation of the physical properties of refrigerant-oil mixtures, including surface tension, again probably accounts for this anomalous behavior. Since no measurements of the physical properties of the R-114-oil mixture were made during this investigation, any possible non-linear property variations of the mixture used are unknown, requiring future work.

B. BOILING PERFORMANCE OF HIGH FLUX SURFACE

Figure 6.4 shows the nucleate pool-boiling performance of the High Flux surface in R-114-oil mixtures. The small magnitude of the wall superheats obtained during nucleate boiling should especially be noted. The High Flux surface in pure R-114 showed typical natural-convection region (A-B) behavior. The incipient point (B) occurred at much lower heat fluxes and superheats than for the smooth tube as shown earlier. The transition to nucleate boiling (B-C) was

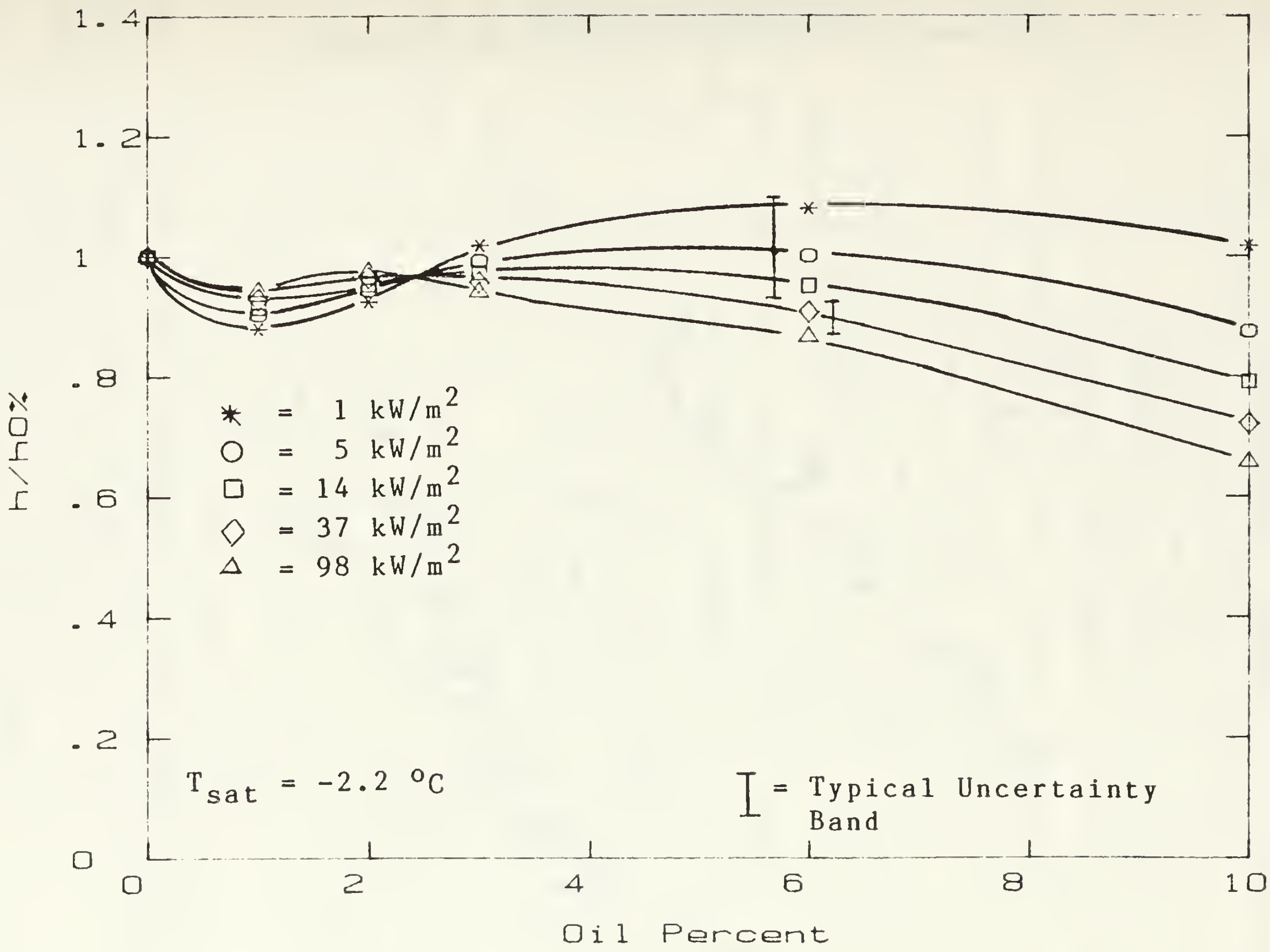


Figure 6.3 Relative Effect of Oil on Smooth Tube Boiling Heat-Transfer Performance.

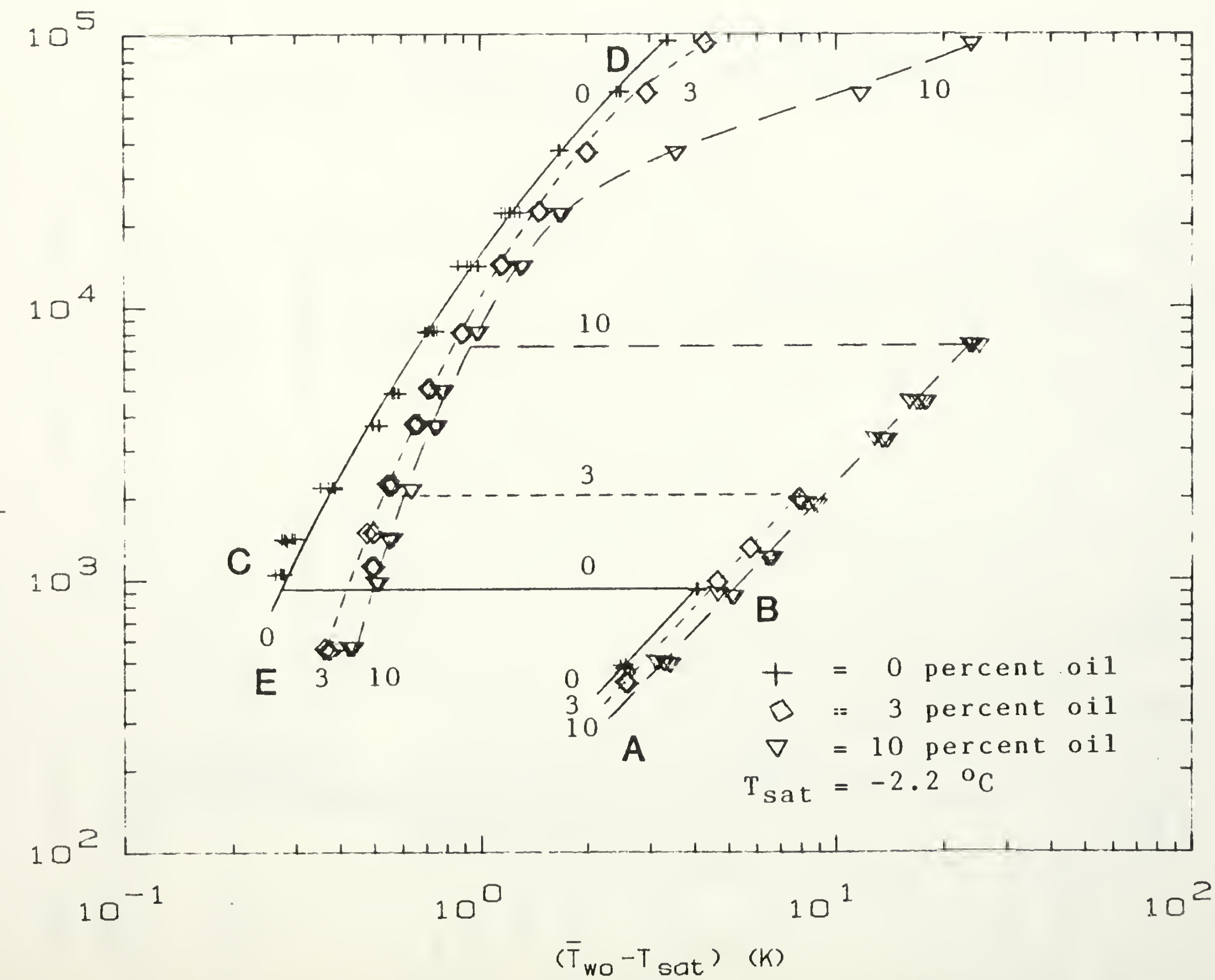


Figure 6.4 Heat-Transfer Performance of High Flux Surface.

similar to the smooth tube, occurring very rapidly (less than 1 second). Nucleate boilng from the High Flux surface results in a drop of the wall superheat by about a factor of 10. This is due to the extremely high density of nucleation sites present on the High Flux surface. From the low heat fluxes (1-10 kW/m^2) at which the transition to nucleate boiling occurs, it can be seen that the High Flux coating also assists in the activation of stable nucleation sites.

Adding oil to the High Flux surface appears to delay the onset of nucleate boiling (point B wall superheat increases with increasing oil concentration). However, the transition to nucleate boiling still occurred very rapidly, even at 10 percent oil. The rapid transition to nucleate boiling (less than 1 second) on the High Flux surface is probably due to the interconnected cavities which can assist in nucleating the entire surface once a single site becomes initially active. Oil is unlikely to inhibit this characteristic of the High Flux surface though it apparently delays the initial activiation of the first nucleation site. As seen in region D-E, for heat fluxes less than 37 kW/m^2, the effect of adding oil to the High Flux surface, once it has been nucleating fully, is to cause about a 30 percent increase in the wall superheat. At heat fluxes in excess of 37 kW/m^2 and at 10 percent oil, the wall superheat increased dramatically. As seen in Figure 6.1, the wall superheat at a heat flux of 98 kW/m^2 and 10 percent oil is about the same for both the smooth tube and High Flux surface.

Figure 6.5 shows the heat-transfer coefficient of the High Flux surface as a function of heat flux for various oil concentrations. Again, oil is seen to degrade the nucleate pool-boiling heat-transfer performance.

Air-conditioning plants typically operate in the heat flux range of 10 to 40 kW/m^2 with less than 1 percent oil. In this region of pracical interest, the boiling

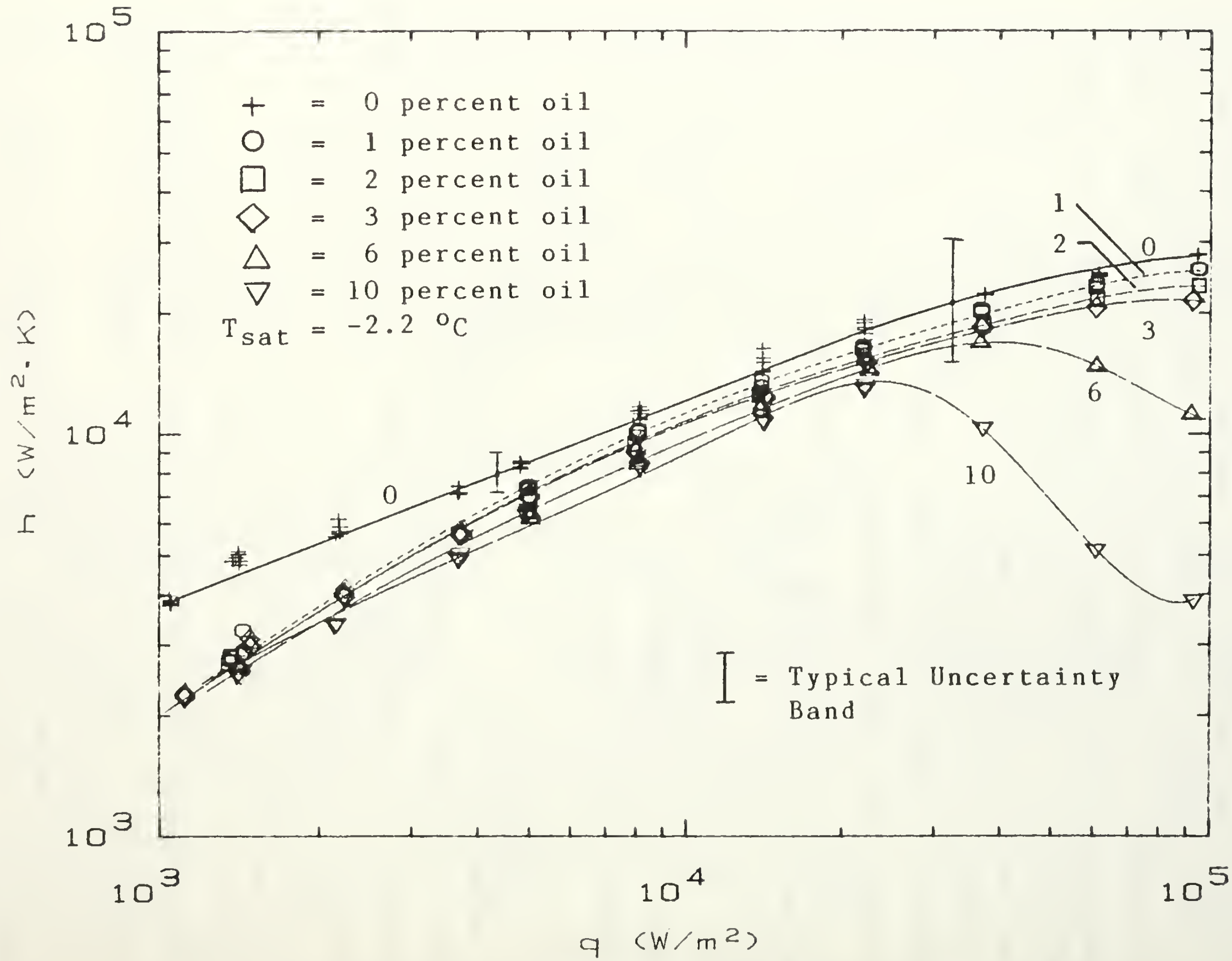


Figure 6.5 **Boiling Heat-Transfer Coefficient of High Flux Surface.**

heat-transfer coefficient of the High Flux surface is about 10 times better than a smooth tube. Also, it experiences only a 20 percent drop in the boiling heat-transfer coefficient with the addition of oil (1 to 10 percent). This is seen clearly in Figure 6.6 which plots the heat-transfer coefficient, relative to the heat-transfer coefficient for 0 percent oil, as a function of oil concentration. From 1 to 10 percent oil at a heat flux of 14 kW/m², the heat-transfer coefficient is about 80 percent of the no-oil heat-transfer coefficient.

Figure 6.6 also shows that the oil-caused degradation of performance on the High Flux surface is nearly independent of oil concentration at practical heat fluxes. Only at a heat fluxof 98 kW/m² and 6-10 percent oil, does the High Flux surface experience significant performance degradation. At high heat fluxes and oil concentrations, the effect of oil may be to "clog" the interconnecting cavities of the High Flux surface due to boiling off of the R-114. Clogging the R-114 surface with oil would prevent replenishment of the nucleation sites with R-114 liquid, preventing the nucleation process and leading to higher superheats. The time-dependent behavior of the High Flux surface in high oil concentrations and at high heat fluxes was not studied in this experiment.

C. COMPARISON OF HIGH FLUX TO SMOOTH TUBE BOILING PERFORMANCE

Figure 6.7 shows the heat-transfer performance of both the High Flux surface and the smooth tube as a function of heat flux. Again, the 7-10 times improvement in the heat-transfer coefficient by the High Flux surface is easily seen. At extremely high heat flux and high oil combinations, the High Flux surface performs only sligthly better than the smooth tube.

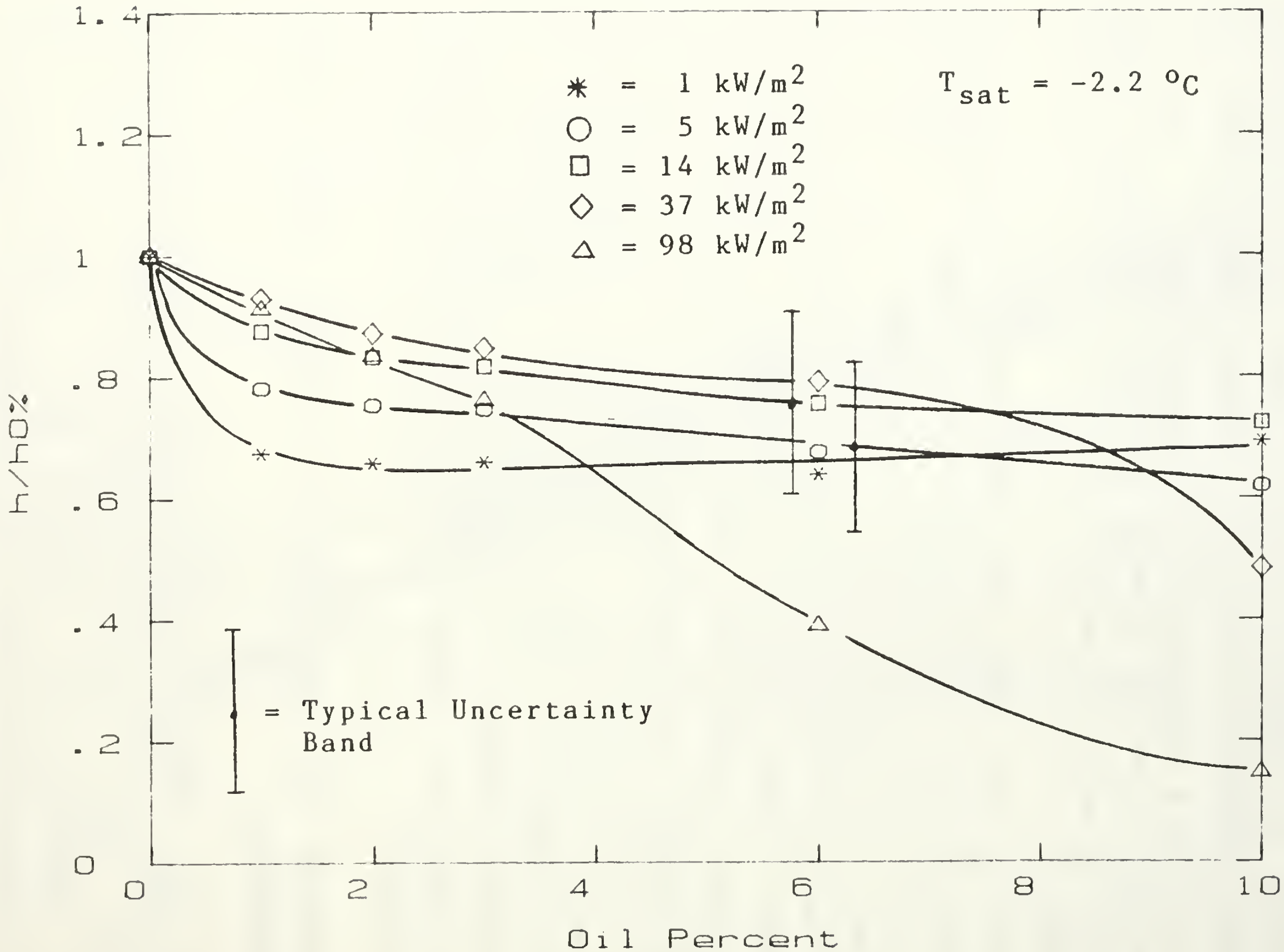


Figure 6.6 Relative Effect of Oil on High Flux Boiling Heat-Transfer Performance.

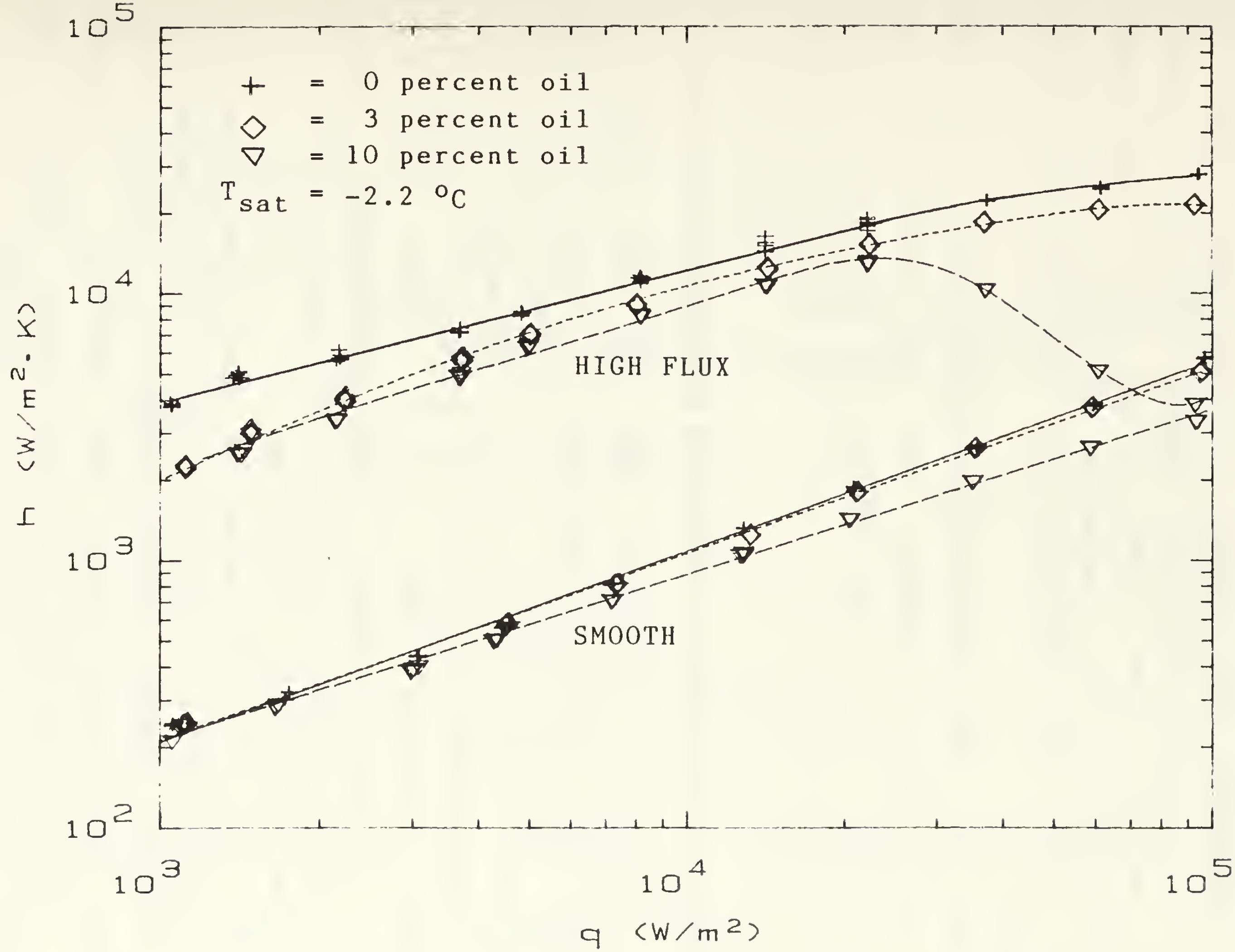


Figure 6.7 Comparison of High Flux and Smooth Tube Boiling Heat-Transfer Performance.

Figure 6.7 also shows that the heat-transfer curves of the High Flux surface and the smooth tube are not parallel. At low heat fluxes, the High Flux surface is more effective, in comparison to the smooth tube, in enhancing nucleation than at moderate heat fluxes. At high heat fluxes, the performance of the High Flux coating begins to converge toward the smooth-tube curve because the surface became vapor blanketed. This is expected since both tubes should perform about the same when they are completely vapor blanketed.

Figure 6.8 shows the relative improvement of the High Flux surface over the smooth tube as a function of oil concentration. For the heat fluxes of practical interest in air-conditioning plants, the High Flux surface is 7-10 times better than the smooth tube.

D. EFFECT OF SATURATION TEMPERATURE ON BOILING PERFORMANCE

As reported by Stephan [Ref. 9], the effect of increasing the saturation temperature for both the smooth tube and High Flux surface was increased heat-transfer performance. Figure 6.9 shows the improvement in heat-transfer performance in pure R-114 achieved by raising the saturation temperature from -2.2 ^{o}C (28 ^{o}F) to 6.7 ^{o}C (44 ^{o}F). At high heat fluxes, little improvement is seen in the High Flux surface performance because the surface is nearly vapor blanketed with bubbles.

Figure 6.10 shows the effect of saturation temperature on R-114-oil mixtures. Increased saturation temperature is again seen to improve the performance of the High Flux surface as well as the smooth tube, even with 10 percent oil. This is consistent with the no-oil results, but contradicts Henrici and Hesse's data (see Figure 2.5).

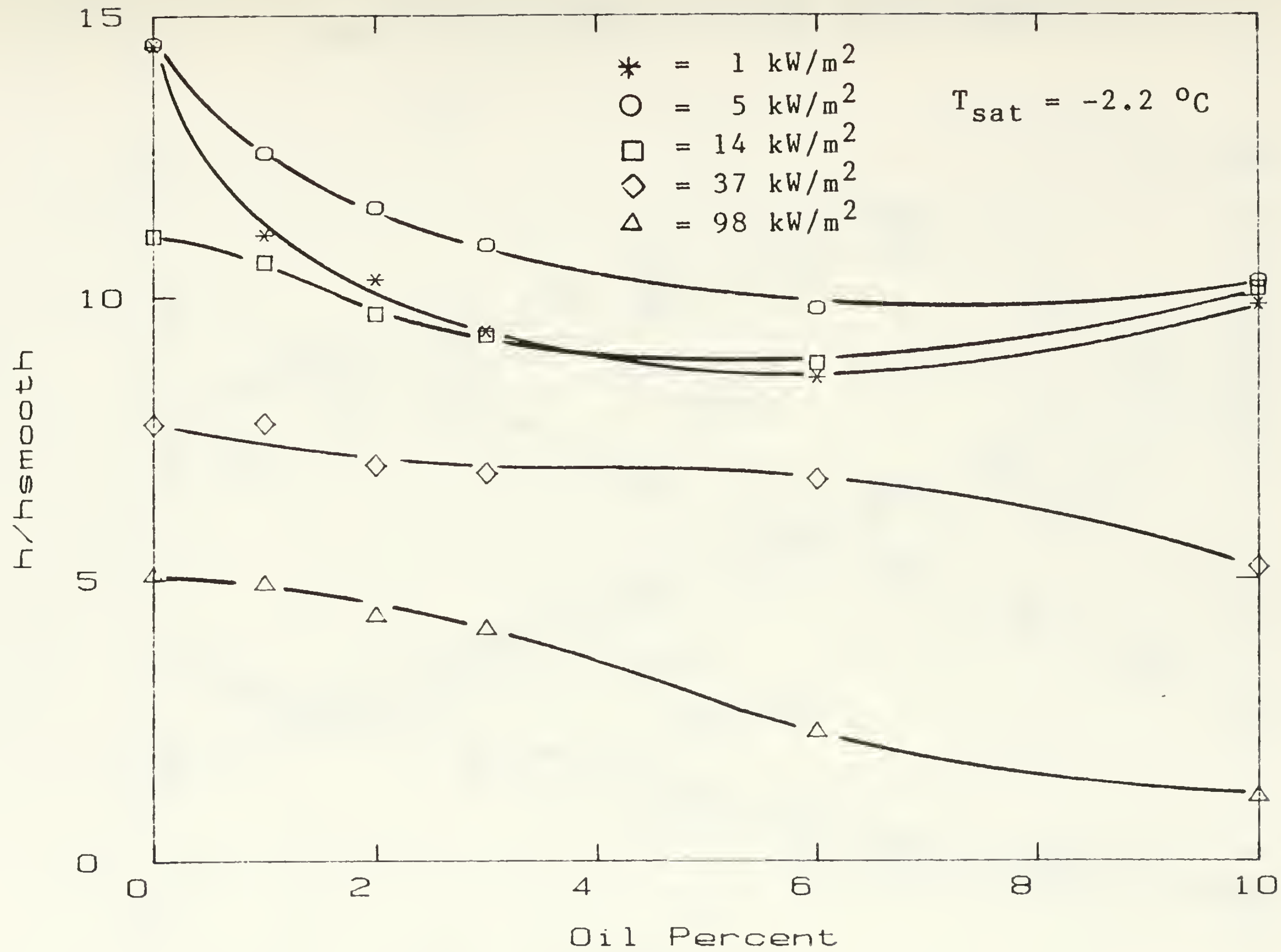


Figure 6.8 Relative Improvement of High Flux Surface over Smooth Tube versus Oil.

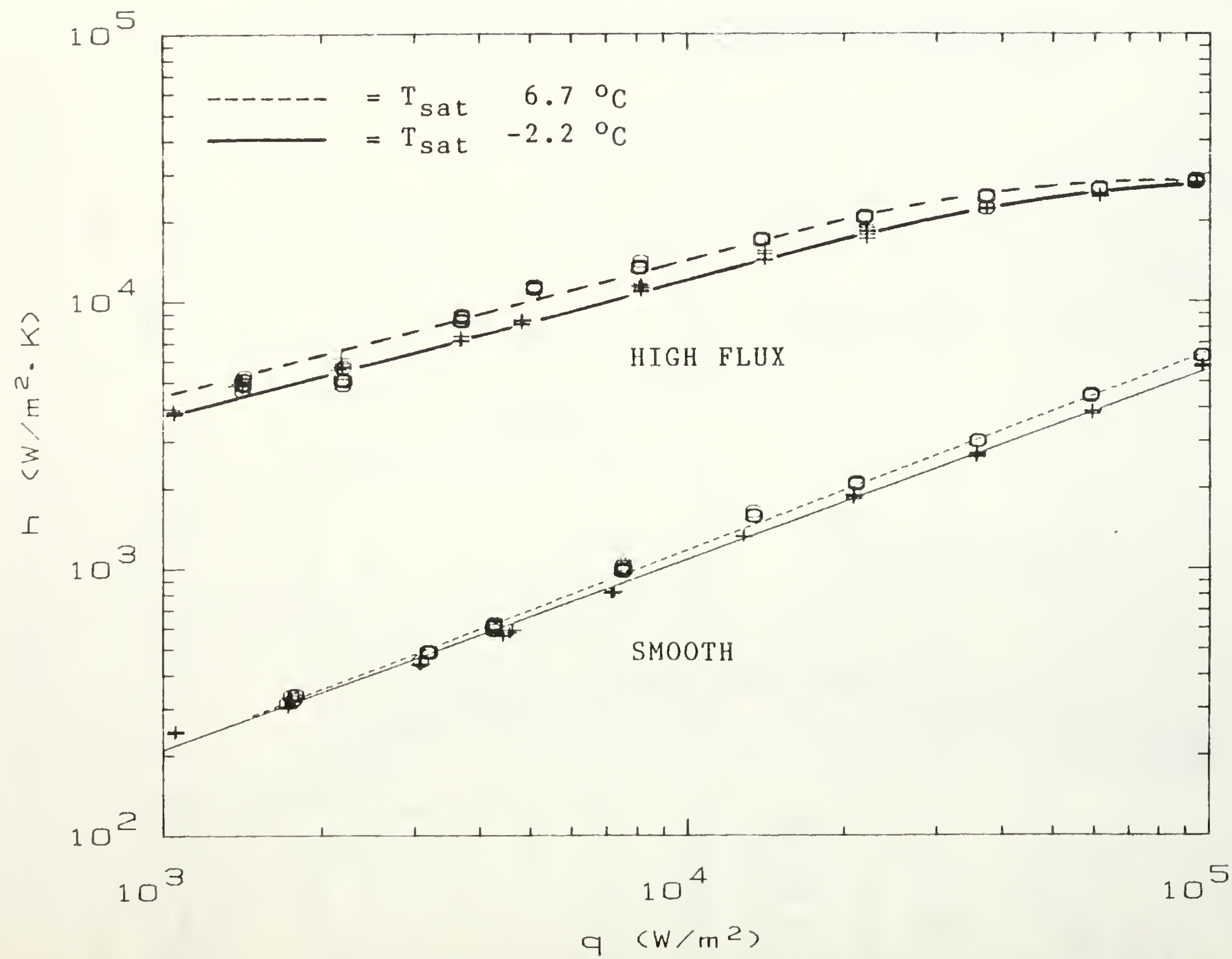


Figure 6.9 Effect of Saturation Temperature on Boiling Heat-Transfer Coefficient.

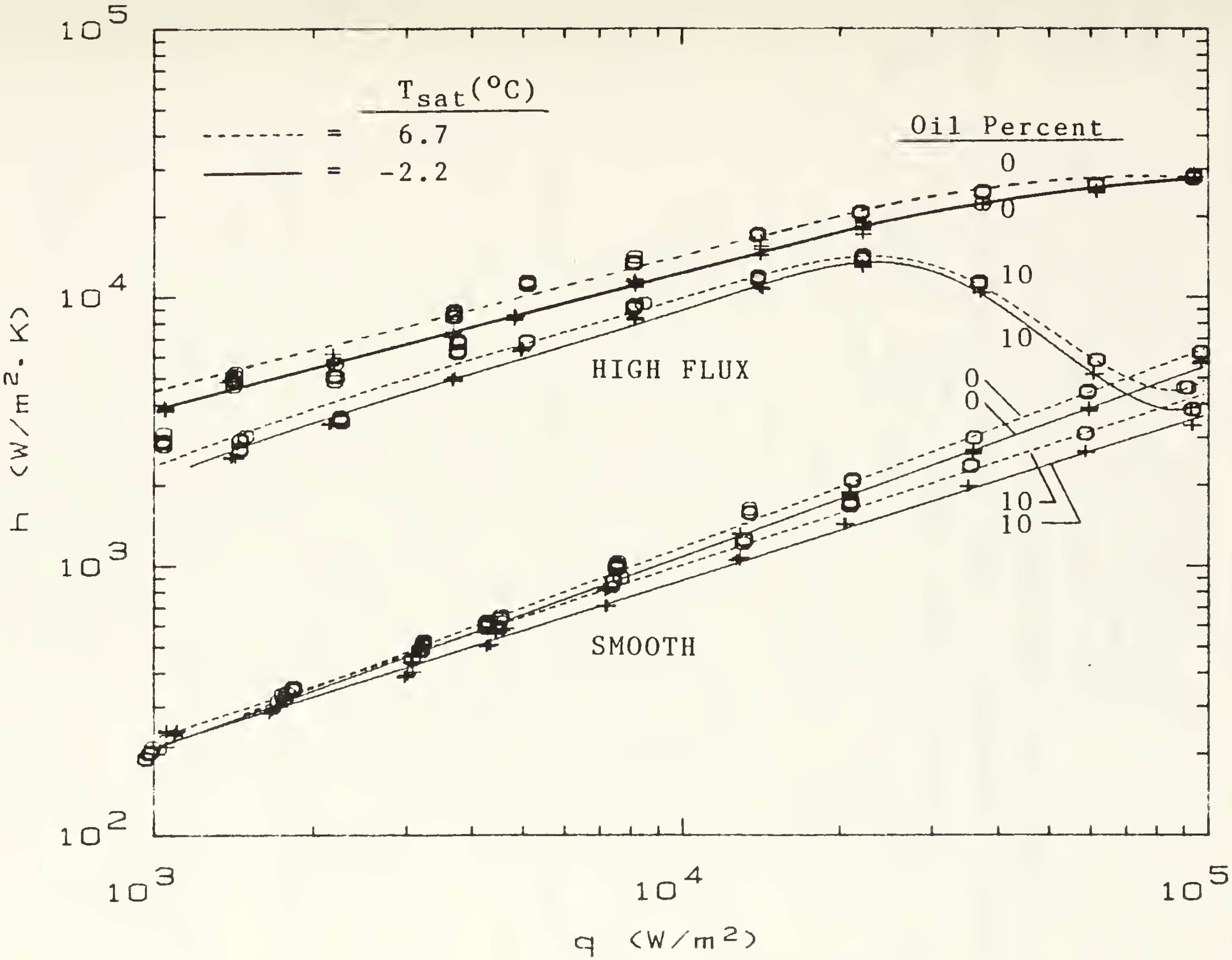


Figure 6.10 Effect of Oil on Variation of Boiling Heat-Transfer Coefficient with Saturation Temperature.

E. LOCAL OIL SAMPLING EFFORTS

The results of the attempt to sample oil locally near the boiling tube were inconclusive. The method outlined in Section IV.C did not produce either repeatable or accurate results. Checks of the sampling method were made by sampling the bulk liquid with 0 and 10 percent oil at zero heat flux. The 0 percent oil check yielded oil concentrations from 0 to 2 percent. The 10 percent oil check yielded oil sample concentrations from 5 to 25 percent.

Further refinements to the sampling apparatus are needed to permit an accurate local sample of oil in the vicinity of a boiling tube. Section VII.B contains recommendations to improve the sampling apparatus.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. In pure R-114, the pool-boiling heat-transfer coefficient of the High Flux surface is about 10 times larger than that of a smooth tube.
2. The High Flux surface began nucleate boiling at low heat fluxes, about 1 kW/m^2, compared to a heat flux of about 10 kW/m^2 for the smooth tube.
3. Oil delayed the onset of nucleate boiling with the High Flux surface.
4. Oil resulted in about a 20 percent reduction in the heat-transfer coefficient of the High Flux surface for most practical heat flux (less than 37 kW/m^2) and oil combinations (less than 6 percent).
5. At heat fluxes of 98 kW/m^2 and greater than 6 percent oil, the performance of the High Flux surface degraded by as much as 80 percent. The performance of the High Flux surface was little better than the smooth tube at 98 kW/m^2 and 10 percent oil.
6. The boiling heat-transfer coefficient of the High Flux surface was about 7 times better than that of a smooth tube for oil concentrations from 1 to 10 percent over the range of heat fluxes employed in air-conditioning plants (10-40 kW/m^2).
7. The boiling heat-transfer coefficient of both the High Flux surface and the smooth tube increased with increasing saturation temperature. The improvement decreased at high heat fluxes for the High Flux surface due to vapor blanketing of the surface.

8. Local oil sample results were not accurate or repeatable enough to determine if a variation in the local oil concentration occurs near a boiling tube.

B. RECOMMENDATIONS

1. The present cartridge heaters should be replaced with more reliable heaters that will produce a uniform heat flux axially at all heat loads.
2. A solid copper tube should be coated with High Flux and tested. Due to the very small superheats of the High Flux surface, even a small amount of contact resistance could affect the data at low heat fluxes.
3. The physical properties of the R-114-oil mixtures tested should be measured to obtain information to better explain the reasons for the heat-transfer performance of both the High Flux surface and the smooth tube. Particularly, the anomalous rise in heat-transfer performance of smooth tubes when 1 to 6 percent oil is present in R-114 should be studied.
4. A secondary heater should be installed in the boiling section to keep the total heat input constant. The heat input to the secondary heater should be increased when the heat input to the boiling tube is decreased and vice versa. This modification will maintain a constant heat load on the condenser and eliminate the need to operate valve VC, except to set the saturation temperature at the beginning of a run. Alternately, the effort to computer control valve VC should continue by obtaining an accurate thermistor with a high temperature resolution for use with the SYS-2A microcomputer. Improved temperature resolution would allow the computer-controlled valve to operate properly and free the operator from the demands of manual control of valve VC.

5. The performance of a bundle of High Flux-coated tubes in R-114-oil mixtures should be studied.
6. Data should be obtained on the High Flux surface over a wider range of temperatures and with oils of varying viscosities.
7. The High Flux surface should be tested for time-dependent heat-transfer performance by taking data periodically over a long time during boiling.
8. A small oil sample container with valves and a vent line should be manufactured. The flexible tubing and pinch clamps used in this experiment did not properly hold or vent the sample.

APPENDIX A

THERMOCOUPLE CALIBRATION

Karasabun [Ref. 8] describes the thermocouple calibration equipment in detail. Two thermocouples were calibrated. One was made from wire at the beginning of the roll, the other from the end of the roll, following the making of all thermocouples used in the apparatus and tests.

Essentially, the manufacturer-supplied calibration equation for the thermocouple wire, a seventh order polynomial, was corrected slightly by adding to it a second order curve fit of the variation of the manufacturer's computed temperature for a given emf from a known set of reference temperatures (measured using a Hewlett-Packard 2804A quartz thermometer with a temperature resolution of ± 0.0001 K and accuracy of ± 0.03 K).

The manufacturer's emf to temperature conversion equation is:

$$T = a_0 + a_1 E + a_2 E^2 + a_3 E^3 + a_4 E^4 + a_5 E^5 + a_6 E^6 + a_7 E^7 \quad (A.1)$$

where

T = temperature (°C)
a_0 = 0.100860910
a_1 = 25727.94369
a_2 = -767345.8295
a_3 = 78025595.81
a_4 = -9247486589
a_5 = 6.97688E+11
a_6 = -2.66192E+13
a_7 = 3.94078E+14
E = thermocouple reading (volts)

Figure A.1 shows the quartz thermometer reading minus the thermocouple readings (discrepancy) versus temperature. The two thermocouples agreed to within 0.05 K of each other and the manufacturer's seventh-order polynomial needed about a 0.1 K increase to more accurately convert the emf's to the true temperature. The correcting second-order polynomial was:

$$DCP = b_0 + b_1 T + b_2 T^2 \qquad (A.2)$$

where

DCP = discrepancy (K)
b_0 = 8.6268968E-2
b_1 = 3.7619902E-3
b_2 = -5.0689259E-5
T = thermocouple reading (from equation A.1) (°C)

Thus, the temperatures computed by the data-reduction program (DRP2) were emf's converted to temperature by equation A.1 with corrections for that temperature computed by equation A.2 added to the temperature to get the true temperature.

Since the data-reduction program utilized differences between thermocouples in all computations, such as wall temperature minus saturation temperature, the corrections above were necessary only for the computation of items dependent on the absclute temperature, like the fluid properties. Appendix E describes in detail the uncertainty analysis and the effect of wall temperature variation on the computation of the heat-transfer coefficient. Thermocouple

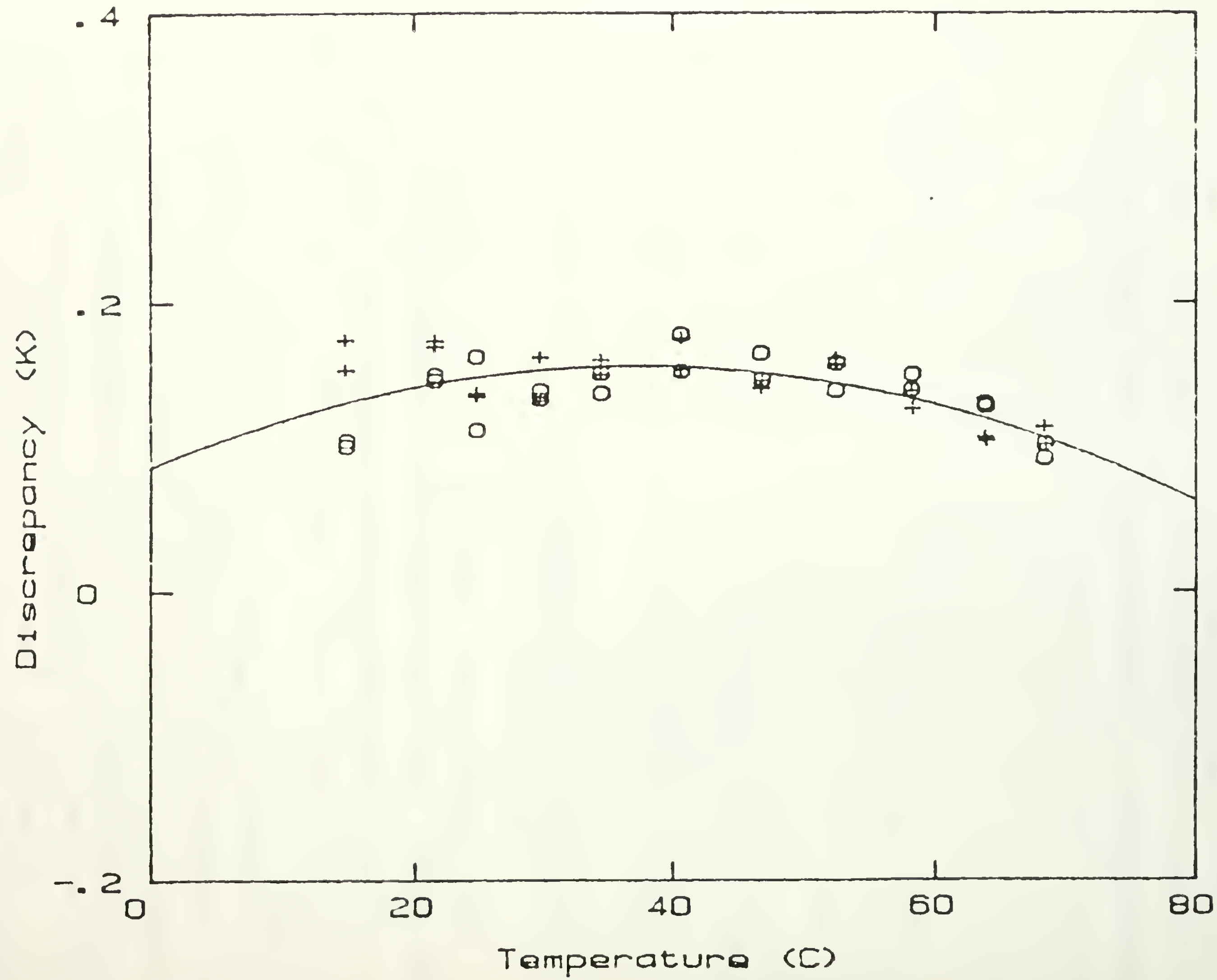


Figure A.1 Thermocouple Discrepancy Correction.

variations of the soft-soldered tubes were most likely due to a slight amount of contact resistance and to the surface characteristics of the tubes tested, since data runs involving shifting the wall thermocouples did not affect the data.

APPENDIX B

DATA REDUCTION PROGRAM

The data reduction program below consists of the following sections:

Main Program	-	Menu of subprogram options
Sub Main	-	Take data or reprocess data
Sub Plot	-	Plot data on log-log scale
Sub Poly	-	Compute least-squares curve fit of data
Sub Plin	-	Plot data on linear-linear scale
Sub Stats	-	Compute average and standard deviation of data

Subprogram Main consists of the following steps:

1. Create data file for data and plot points.
2. Select tube type.
3. Monitor heat flux or saturation temperature to establish steady-state conditions.
4. Scan all channels listed in Table 2 and save in data file.
5. Convert raw emf's to temperatures, current, and voltage.
6. Compute the heat-transfer rate for the cartridge hater.
7. Compute the average wall temperature, the wall superheat, and the film temperature.
8. Compute the physical properties of R-114 using given correlations at film temperature.
9. Compute the natural-convection heat-transfer coefficient of R-114 for the non-boiling ends of the test tube.
10. Compute the heat loss from the non-boiling ends.

11. Calculate the corrected heat flux from the test tube to the liquid R-114.
12. Calculate the boiling heat-transfer coefficient of the R-114 from the test tube.
13. Print data. Store heat flux and wall superheat values in plot file.

The following is a listing of the complete data reduction program (DRP2) written in Basic 3.0 for the Hewlett-Packard 9826 computer.

```
1000! FILE NAME: DRP2
1005! DATE:      October 19, 1984
1010! REVISED:   March 10, 1985
1015!
1020  BEEP
1025  PRINTER IS 1
1030  PRINT USING "4X ""Select option:"""
1035  PRINT USING "6X ""0 Taking data or re-processing previous data"""
1040  PRINT USING "6X,""1 Plotting data on Log-Log """
1045  PRINT USING "6X,""2 Plotting data on Linear"""
1050  PRINT USING "6X,""3 Make cross-plot coefft file"""
1055  INPUT Ido
1060  IF Ido=0 THEN CALL Main
1065  IF Ido=1 THEN CALL Plot
1070  IF Ido=2 THEN CALL Plin
1075  IF Ido=3 THEN CALL Coef
1080  END
1085  SUB Main
1090  COM /Cc/ C(7),Ical
1095  DIM Emf(12),T(12),D1a(6),D2a(6),Dia(6),Doa(6),La(6),Lua(6),Kcua(6)
1100  DATA 0.10006091,25727.94369,-767345.8295,78025595.81
1105  DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1110  READ C(*)
1115  PRINTER IS 701
1120  CLEAR 709
1125  BEEP
1130  INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1135  OUTPUT 709;"TD";Date$
1140  OUTPUT 709;"TD"
1145  ENTER 709;Date$
1150  PRINT
1155  PRINT "             Month, date and time :";Date$
1160  PRINT
1165  PRINT USING "10X,""NOTE: Program name : DRP2"""
1170  BEEP
1175  INPUT "ENTER DISK NUMBER",Dn
1180  PRINT USING "16X,""Disk number  = "",ZZ";Dn
1185  BEEP
1190  INPUT "ENTER INPUT MODE (0=3054A,1=FILE)",Im
1195  BEEP
1200  INPUT "ENTER THERMOCOUPLE TYPE (0=NEW,1=OLD)",Ical
1205  IF Im=0 THEN
1210  BEEP
1215  INPUT "GIVE A NAME FOR THE RAW DATA FILE",D2_file$
1220  PRINT USING "16X,""New file name: "",14A";D2_file$
1225  BEEP
1230  INPUT "INPUT SIZE OF FILE BDAT",Size1
1235  CREATE BDAT D2_file$,Size1
1240  ASSIGN @File2 TO D2_file$
1245!
1250! DUMMY FILE UNTIL Nrun KNOWN
1255  D1_file$="DUMMY"
1260  CREATE BDAT D1_file$,Size1
1265  ASSIGN @File1 TO D1_file$
1270  OUTPUT @File1;Date$
```

```
1275  BEEP
1280  INPUT "GIVE A NAME FOR THE PLOT FILE" P_file$
1285  BEEP
1290  INPUT "INPUT SIZE OF FILE BDAT",Size2
1295  CREATE BDAT P_file$ Size2
1300  ASSIGN @Plot TO P_file$
1305  BEEP
1310  INPUT "ENTER NUMBER OF DEFECTIVE TCS (0=DEFAULT)",Idtc
1315  IF Idtc=0 THEN
1320  Ldtc1=0
1325  Ldtc2=0
1330  PRINT USING "16X,""No defective TCs exist"""
1335  END IF
1340  IF Idtc=1 THEN
1345  BEEP
1350  INPUT "ENTER DEFECTIVE TC LOCATION",Ldtc1
1355  PRINT USING "16X,""TC is defective at location "",D";Ldtc1
1360  Ldtc2=0
1365  END IF
1370  IF Idtc=2 THEN
1375  BEEP
1380  INPUT "ENTER DEFECTIVE TC LOCATIONS",Ldtc1,Ldtc2
1385  PRINT USING "16X,""TC are defective at locations "",D,4X,D";Ldtc1,Ldtc2
1390  END IF
1395  IF Idtc>2 THEN
1400  BEEP
1405  PRINTER IS 1
1410  BEEP
1415  PRINT "INVALID ENTRY"
1420  PRINTER IS 701
1425  GOTO 1305
1430  END IF
1435  OUTPUT @File1;Ldtc1,Ldtc2
1440! Im=1 option
1445  ELSE
1450  BEEP
1455  INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D2_file$
1460  PRINT USING "16X,""Old file name: "",14A";D2_file$
1465  ASSIGN @File2 TO D2_file$
1470  ENTER @File2;Nrun
1475  ENTER @File2;Dold$
1480  BEEP
1485  INPUT "GIVE A NAME FOR PLOT FILE",P_file$
1490  BEEP
1495  INPUT "INPUT SIZE OF FILE BDAT",Size2
1500  CREATE BDAT P_file$,Size2
1505  ASSIGN @Plot TO P_file$
1510  PRINT USING "16X,""This data set taken on : "",14A";Dold$
1515  ENTER @File2;Ldtc1,Ldtc2
1520  IF Ldtc1<>0 OR Ldtc2<>0 THEN
1525  PRINT USING "16X,""Thermocouples were defective at locations:"",2(3D,4X)";
Ldtc1,Ldtc2
1530  END IF
1535  ENTER @File2;Itt
1540  END IF
1545  PRINTER IS 1
1550  IF Im=0 THEN
1555  BEEP
1560  PRINT USING "4X,""Select tube type"""
1565  PRINT USING "6X,""0=Smooth 4 inch Ref"""
1570  PRINT USING "6X,""1=Smooth 4 inch Cu (Press/Slide)"""
1575  PRINT USING "6X,""2=Soft Solder 4 inch Cu"""
1580  PRINT USING "6X,""3=Soft Solder 4 inch HIGH FLUX"""
1585  PRINT USING "6X,""4=Wieland Hard 8 inch"""
1590  PRINT USING "6X,""5=HIGH FLUX 8 inch"""
1595  PRINT USING "6X,""6=GEWA-K 19 F/in"""
1600  INPUT Itt
1605  IF Itt>6 THEN
1610  BEEP
1615  PRINT "INVALID ENTRY"
1620  GOTO 1560
1625  END IF
1630  OUTPUT @File1;Itt
1635  END IF
1640  PRINTER IS 701
1645  PRINT USING "16X,""Tube Type:      "",D";Itt
```

```
1650  BEEP
1655  INPUT "ENTER OUTPUT VERSION (0=LONG,1=SHORT,2=NONE)",Iov
1660!
1665! D1=Diameter at thermocouple positions
1670  DATA .0111125,.0111125,.0111125,.0129540,.012446,.0129540,.0100965
1675  READ D1a(*)
1680  D1=D1a(Itt)
1685!
1690! D2=Diameter of test section to the base of fins
1695  DATA .015875,.015875,.015875,.015824,.015875,.015824,.01270
1700  READ D2a(*)
1705  D2=D2a(Itt)
1710!
1715! Di=Inside diameter of unenhanced ends
1720  DATA .0127,.0127,.0127,.0132,.0127,.0132,.0111125
1725  READ Dia(*)
1730  Di=Dia(Itt)
1735!
1740! Do=Outside diameter of unenhanced ends
1745  DATA .015875,.015875,.015875,.015824,.015875,.015824,.01270
1750  READ Doa(*)
1755  Do=Doa(Itt)
1760!
1765! L=Length of enhanced surface
1770  DATA .1016,.1016,.1016,.1016,.2032,.2032,.2032
1775  READ La(*)
1780  L=La(Itt)
1785!
1790! Lu=Length of unenhanced surface at the ends
1795  DATA .0254,.0254,.0254,.0254,.0762,.0762,.0762
1800  READ Lua(*)
1805  Lu=Lua(Itt)
1810!
1815! Kcu=Thermal Conductivity of tube
1820  DATA 398,344,344,45,344,45,344
1825  READ Kcua(*)
1830  Kcu=Kcua(Itt)
1835  A=PI*(Do^2-Di^2)/4
1840  P=PI*Do
1845  J=1
1850  Sx=0
1855  Sy=0
1860  Sxs=0
1865  Sxy=0
1870 Repeat: !
1875  IF Im=0 THEN
1880  ON KEY 0,15 RECOVER 1870
1885  PRINTER IS 1
1890  PRINT USING "4X,""SELECT OPTION"""
1895  PRINT USING "6X,""0=TAKE DATA"""
1900  PRINT USING "6X,""1=SET HEAT FLUX"""
1905  PRINT USING "6X,""2=SET Tsat"""
1910  PRINT USING "4X,""NOTE: KEY 0 = ESCAPE"""
1915  BEEP
1920  INPUT Ido
1925  IF Ido=0 THEN 2495
1930!
1935! LOOP TO SET HEAT FLUX
1940  IF Ido=1 THEN
1945  OUTPUT 709;"AR AF62 AL63 VRS"
1950  BEEP
1955  INPUT "ENTER DESIRED Qdo",Dqdo
1960  PRINT USING "4X,""DESIRED Qdo  ACTUAL Qdo"""
1965  Err=1000
1970  FOR I=1 TO 2
1975  OUTPUT 709;"AS SA"
```

```
1980  Sum=0
1985  FOR Ji=1 TO 5
1990  ENTER 709;E
1995  Sum=Sum+E
2000  NEXT Ji
2005  IF I=1 THEN Volt=Sum*5
2010  IF I=2 THEN Amp=E
2015  NEXT I
2020  Aqdo=Volt*Amp/(PI*D2*L)
2025  IF ABS(Aqdo-Dqdo) Err THEN
2030  IF Aqdo>Dodp THEN
2035  BEEP 4000,.2
2040  BEEP 4000,.2
2045  BEEP 4000,.2
2050  ELSE
2055  BEEP 250,.2
2060  BEEP 250,.2
2065  BEEP 250,.2
2070  END IF
2075  PRINT USING "4X,MZ.3DE,2X,MZ.3DE";Dqdp,Aqdp
2080  WAIT 2
2085  GOTO 1970
2090  ELSE
2095  BEEP
2100  PRINT USING "4X,MZ.3DE,2X,MZ.3DE";Dqdp,Aqdp
2105  Err=500
2110  WAIT 2
2115  GOTO 1970
2120  END IF
2125  END IF
2130!
2135! LOOP TO SET Tsat
2140  IF Ido=2 THEN
2145  BEEP
2150  INPUT "ENTER DESIRED Tsat",Dtld
2155  PRINT USING "4X,""  DTsat   ATsat    Rate     Tv      Rate"""
2160  Old1=0
2165  Old2=0
2170  OUTPUT 709;"AR AF33 AL35 VR5"
2175  FOR I=1 TO 3
2180  Sum=0
2185  OUTPUT 709;"AS SA"
2190  FOR Ji=1 TO 2
2195  ENTER 709;Eliq
2200  Sum=Sum+Eliq
2205  NEXT Ji
2210  Eliq=Sum/2
2215  Tld=FNTvsv(Eliq)
2220  IF I=1 THEN Atld=Tld
2225  IF I=3 THEN Tv=Tld
2230  NEXT I
2235  IF ABS(Atld-Dtld)>.2 THEN
2240  IF Atld>Dtld THEN
2245  BEEP 4000,.2
2250  BEEP 4000,.2
2255  BEEP 4000,.2
2260  ELSE
2265  BEEP 250,.2
2270  BEEP 250,.2
2275  BEEP 250,.2
2280  END IF
2285  Err1=Atld-Old1
2290  Old1=Atld
2295  Err2=Tv-Old2
2300  Old2=Tv
2305  PRINT USING "4X,5(MDD.DD,1X)";Dtld,Atld,Err1,Tv,Err2
```

```
2310  WAIT 2
2315  GOTO 2170
2320  ELSE
2325  IF ABS(Atld-Otld)>.1 THEN
2330  IF Atld>Otld THEN
2335  BEEP 3000,.2
2340  BEEP 3000,.2
2345  ELSE
2350  BEEP 800,.2
2355  BEEP 800,.2
2360  END IF
2365  Err1=Atld-Old1
2370  Old1=Atld
2375  Err2=Tv-Old2
2380  Old2=Tv
2385  PRINT USING "4X,5(MDD.DD,1X)";Otld,Atld,Err1,Tv,Err2
2390  WAIT 2
2395  GOTO 2170
2400  ELSE
2405  BEEP
2410  Err1=Atld-Old1
2415  Old1=Atld
2420  Err2=Tv-Old2
2425  Old2=Tv
2430  PRINT USING "4X,5(MDD.DD,1X)";Otld,Atld,Err1,Tv,Err2
2435  WAIT 2
2440  GOTO 2170
2445  END IF
2450  END IF
2455  END IF
2460! ERROR TRAP FOR Ido OUT OF BOUNDS
2465  IF Ido>2 THEN
2470  BEEP
2475  GOTO 1890
2480  END IF
2485!
2490! TAKE DATA IF Im=0 LOOP
2495  BEEP
2500  INPUT "ENTER BULK OIL %",Boo
2505  OUTPUT 709;"AR AF25 AL36 VR5"
2510  FOR I=1 TO 12
2515  OUTPUT 709;"AS SA"
2520  Sum=0
2525  FOR J1=1 TO 2
2530  ENTER 709;E
2535  Sum=Sum+E
2540  NEXT J1
2545  Emf(I)=Sum/2
2550  NEXT I
2555  OUTPUT 709;"AR AF62 AL63 VR5"
2560  FOR I=1 TO 2
2565  OUTPUT 709;"AS SA"
2570  Sum=0
2575  FOR J1=1 TO 2
2580  ENTER 709;E
2585  Sum=Sum+E
2590  NEXT J1
2595  IF I=1 THEN Vr=Sum/2
2600  IF I=2 THEN Ir=Sum/2
2605  NEXT I
2610  ELSE
2615  ENTER @File2;Boo,Told$,Emf(*),Vr,Ir
2620  END IF
2625!
2630! CONVERT emf'S TO TEMP,VOLT,CURRENT
2635  Twa=0
```

```
2640  FOR I=1 TO 12
2645  IF Idtc>0 THEN
2650  IF I=Ldtc1 OR I=Ldtc2 THEN
2655  T(I)=-99.99
2660  GOTO 2710
2665  END IF
2670  END IF
2675  IF Itt<4 THEN
2680  IF I>4 AND I<9 THEN
2685  T(I)=-99.99
2690  GOTO 2710
2695  END IF
2700  END IF
2705  T(I)=FNTvsv(Emf(I))
2710  NEXT I
2715  IF Itt<4 THEN
2720  FOR I=1 TO 4
2725  IF I=Ldtc1 OR I=Ldtc2 THEN
2730  Twa=Twa
2735  ELSE
2740  Twa=Twa+T(I)
2745  END IF
2750  NEXT I
2755  Twa=Twa/(4-Idtc)
2760  ELSE
2765  FOR I=1 TO 8
2770  IF I=Ldtc1 OR I=Ldtc2 THEN
2775  Twa=Twa
2780  ELSE
2785  Twa=Twa+T(I)
2790  END IF
2795  NEXT I
2800  Twa=Twa/(8-Idtc)
2805  END IF
2810  Tld=T(9)
2815  Tld2=T(10)
2820  Tv=T(11)
2825  IF Itt 3 THEN
2830  Tld2=-99.99
2835  Tv=(T(10)+T(11))/2
2840  END IF
2845  Tsumo=T(12)
2950  Amo=Ir
2855  Volt=Vr*25
2860  Q=Volt*Amo
2865  IF Itt=0 THEN
2870  Kcu=FNKcu(Twa)
2875  ELSE
2880  Kcu=Kcua(Itt)
2885  END IF
2890!
2895! FOURIER CONDUCTION EQUATION WITH CONTACT RESISTANCE NEGLECTED
2900  Tw=Twa-Q*LOG(D2/D1)/(2*PI*Kcu*L)
2905  Thetab=Tw-Tld
2910  IF Thetab<0 THEN
2915  BEEP
2920  INPUT "TWALL TSAT (0=CONTINUE, 1=END)",Iev
2925  IF Iev=0 THEN GOTO 1875
2930  IF Iev=1 THEN 3330
2935  END IF
2940!
2945! COMPUTE VARIOUS PROPERTIES
2950  Tfilm=FNTfilm(Tw,Tld)
2955  Rho=FNRho(Tfilm)
2960  Mu=FNMu(Tfilm)
2965  K=FNK(Tfilm)
```

```
2970  Co=FNCo(Tfilm)
2975  Beta=FNBeta(Tfilm)
2980  Ni=Mu/Rho
2985  Alpha=K/(Rho*Co)
2990  Pr=Ni/Alpha
2995  Psat=FNPsat(Tld)
3000!
3005! COMPUTE NATURAL-CONVECTIVE HEAT-TRANSFER COEFFICIENT
3010! FOR UNENHANCED END(S)
3015  Hbar=190
3020  Fe=(Hbar*P/(Kcu*A))^.5*Lu
3025  Tanh=FNTanh(Fe)
3030  Theta=Thetab*Tanh/Fe
3035  Xx=(9.81*Beta*Thetab*Do^3*Tanh/(Fe*Ni*Alpha))^.166667
3040  Yy=(1+(.559/Pr)^(9/16))^(8/27)
3045  Hbarc=K/Do*(.6+.387*Xx/Yy)^2
3050  IF ABS((Hbar-Hbarc)/Hbarc)>.001 THEN
3055  Hbar=(Hbar+Hbarc)*.5
3060  GOTO 3020
3065  END IF
3070!
3075! COMPUTE HEAT LOSS RATE THROUGH UNENHANCED END(S)
3080  Ql=(Hbar*P*Kcu*A)^.5*Thetab*Tanh
3085  Qc=Q-2*Ql
3090  As=PI*D2*L
3095!
3100! COMPUTE ACTUAL HEAT FLUX AND BOILING COEFFICIENT
3105  Qdo=Qc/As
3110  Htube=Qdo/Thetab
3115!
3120! RECORD TIME OF DATA TAKING
3125  IF Im=0 THEN
3130  OUTPUT 709;"TD"
3135  ENTER 709;Told$
3140  END IF
3145!
3150! OUTPUT DATA TO PRINTER
3155  PRINTER IS 701
3160  IF Iov=0 THEN
3165  PRINT
3170  PRINT USING "10X,""Data Set Number = "",DDD,2X,""Bulk Oil % = "",DD.D,5X,1
4A";J,Bop,Told$
3175  PRINT
3180  PRINT USING "10X,""TC No:     1       2       3       4       5       6       7
    8"""
3185  PRINT USING "10X,""Temp :"",8(1X,MDD.DD)";T(1),T(2),T(3),T(4),T(5),T(6),T(
7),T(8)
3190  PRINT USING "10X,"" Twa     Tliqd   Tliqd2  Tvapr  Psat   Tsump"""
3195  PRINT USING "10X,2(MDD.DD,1X),1X,MDD.DD,1X,2(1X,MDD.DD),2X,MDD.D";Twa,Tld,
Tld2,Tv,Psat,Tsump
3200  PRINT USING "10X,"" Thetab  Htube      Qdo"""
3205  PRINT USING "10X,MDD.3D,1X,MZ.3DE,1X,MZ.3DE";Thetab,Htube,Qdo
3210  END IF
3215  IF Iov=1 THEN
3220  IF J=1 THEN
3225  PRINT
3230  PRINT USING "10X,""RUN No Oil%  Tsat   Htube      Qdo         Thetab"""
3235  END IF
3240  PRINT USING "12X,3D,4X,DD,2X,MDD.DD,3(1X,MZ.3DE)";J,Bop,Tld,Htube,Qdo,Thet
ab
3245  END IF
3250  IF Im=0 THEN
3255  BEEP
3260  INPUT "OK TO STORE THIS DATA SET (1=Y,0=N)?",Ok
3265  END IF
3270  IF Ok=1 OR Im=1 THEN J=J+1
```

```
3275  IF Ok=1 AND Im=0 THEN OUTPUT @File1;Boo,Told$,Emf(*),Vr,Ir
3280  IF Im=1 OR Ok=1 THEN OUTPUT @Plot;Odo,Thetab
3285  IF Im=0 THEN
3290  BEEP
3295  INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
3300  Nrun=J
3305  IF Go_on<>1 THEN 3330
3310  IF Go_on=1 THEN Reoeat
3315  ELSE
3320  IF J<Nrun+1 THEN Reoeat
3325  ENO IF
3330  IF Im=0 THEN
3335  BEEP
3340  PRINT USING "10X,""NOTE: "",ZZ,"" data runs were stored in file "",10A";J-
1,D2_file$
3345  ASSIGN @File1 TO *
3350  OUTPUT @File2;Nrun-1
3355  ASSIGN @File1 TO D1_file$
3360  ENTER @File1;Date$,Ldtc1,Ldtc2,Itt
3365  OUTPUT @File2;Date$,Ldtc1,Ldtc2,Itt
3370  FOR I=1 TO Nrun-1
3375  ENTER @File1;Boo,Told$,Emf(*),Vr,Ir
3380  OUTPUT @File2;Boo,Told$,Emf(*),Vr,Ir
3385  NEXT I
3390  ASSIGN @File1 TO *
3395  PURGE "OUMMY"
3400  ENO IF
3405  BEEP
3410  PRINT USING "10X,""NOTE: "",ZZ,"" X-Y pairs were stored in plot data file
"" 10A";J-1,P_file$
3415  ASSIGN @File2 TO *
3420  ASSIGN @Plot TO *
3425  CALL Stats
3430  BEEP
3435  INPUT "LIKE TO PLOT DATA (1=Y,0=N)?",Ok
3440  IF Ok=1 THEN
3445  CALL Plot
3450  END IF
3455  SUBEND
3460!
3465! CURVE FITS OF PROPERTY FUNCTIONS
3470  DEF FNKcu(T)
3475! OFHC COPPER 250 TO 300 K
3480  Tk=T+273.15      !C TO K
3485  K=434-.112*Tk
3490  RETURN K
3495  FNEND
3500  DEF FNMu(T)
3505! 170 TO 360 K CURVE FIT OF VISCOUSITY
3510  Tk=T+273.15      !C TO K
3515  Mu=EXP(-4.4636+(1011.47/Tk))*1.0E-3
3520  RETURN Mu
3525  FNENO
3530  DEF FNCo(T)
3535! 180 TO 400 K CURVE FIT OF Co
3540  Tk=T+273.15      !C TO K
3545  Cp=.40188+1.65007E-3*Tk+1.51494E-6*Tk^2-6.67853E-10*Tk^3
3550  Co=Co*1000
3555  RETURN Co
3560  FNEND
3565  DEF FNRho(T)
3570  Tk=T+273.15      !C TO K
3575  X=1-(1.8*Tk/753.95)  !K TO R
3580  Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^.5+1.119828*X^2
3585  Ro=Ro/.062428
3590  RETURN Ro
```

```
3595  FNEND
3600  DEF FNPr(T)
3605  Pr=FNCp(T)*FNMu(T)/FNK(T)
3610  RETURN Pr
3615  FNEND
3620  DEF FNK(T)
3625! T<360 K WITH T IN C
3630  K=.071-.000261*T
3635  RETURN K
3640  FNEND
3645  DEF FNTanh(X)
3650  P=EXP(X)
3655  Q=1/P
3660  Tanh=(P-Q)/(P+Q)
3665  RETURN Tanh
3670  FNEND
3675  DEF FNTvsv(V)
3680  COM /Cc/ C(7),Ical
3685  T=C(0)
3690  FOR I=1 TO 7
3695  T=T+C(I)*V^I
3700  NEXT I
3705  IF Ical=1 THEN
3710  T=T-6.7422934E-2+T*(9.0277043E-3-T*(-9.3259917E-5))
3715  ELSE
3720  T=T+8.626897E-2+T*(3.76199E-3-T*5.0689259E-5)
3725  END IF
3730  RETURN T
3735  FNEND
3740  DEF FNBeta(T)
3745  Rop=FNRho(T+.1)
3750  Rom=FNRho(T-.1)
3755  Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
3760  RETURN Beta
3765  FNEND
3770  DEF FNTfilm(Tw,Tld)
3775  Tfilm=(Tw+Tld)/2
3780  RETURN Tfilm
3785  FNEND
3790  DEF FNPsat(Tc)
3795! 0 TO 80 deg F CURVE FIT OF Psat
3800  Tf=1.8*Tc+32
3805  Pa=5.945525+Tf*(.15352082+Tf*(1.4840963E-3+Tf*9.6150671E-6))
3810  Pg=Pa-14.7
3815  IF Pg>0 THEN        ! +=PSIG,-=in Hg
3820  Psat=Pg
3825  ELSE
3830  Psat=Pg*29.92/14.7
3835  END IF
3840  RETURN Psat
3845  FNEND
3850  SUB Plot
3855  COM /Colv/ A(10,10),C(10),B(4),Nop,Iprnt,Opo,Ilog
3860  INTEGER Ii
3865  PRINTER IS 1
3870  BEEP
3875  INPUT "LIKE DEFAULT VALUES FOR PLOT (1=Y,0=N)?",Idv
3880  BEEP
3885  PRINT USING "4X,""Select Option:"""
3890  PRINT USING "6X,""0  q versus delta-T"""
3895  PRINT USING "6X,""1  h versus delta-T"""
3900  PRINT USING "6X,""2  h versus q"""
3905  INPUT Opo
3910  BEEP
3915  INPUT "SELECT UNITS (0=SI,1=ENGLISH)",Iun
3920  PRINTER IS 705
```

```
3925  IF Idv<>1 THEN
3930  BEEP
3935  INPUT "ENTER NUMBER OF CYCLES FOR X-AXIS",Cx
3940  BEEP
3945  INPUT "ENTER NUMBER OF CYCLES FOR Y-AXIS",Cy
3950  BEEP
3955  INPUT "ENTER MIN X-VALUE (MULTIPLE OF 10)",Xmin
3960  BEEP
3965  INPUT "ENTER MIN Y-VALUE (MULTIPLE OF 10)",Ymin
3970  ELSE
3975  IF Ooo=0 THEN
3980  Cy=3
3985  Cx=3
3990  Xmin=.1
3995  Ymin=100
4000  END IF
4005  IF Ooo=1 THEN
4010  Cy=3
4015  Cx=3
4020  Xmin=.1
4025  Ymin=100
4030  END IF
4035  IF Ooo=2 THEN
4040  Cy=3
4045  Cx=2
4050  Xmin=1000
4055  Ymin=100
4060  END IF
4065  END IF
4070  BEEP
4075  PRINT "IN;SP1;IP 2300,2200,8300,6800;"
4080  PRINT "SC 0,100,0,100;TL 2,0;"
4085  Sfx=100/Cx
4090  Sfy=100/Cy
4095  PRINT "PU 0,0 PD"
4100  Nn=9
4105  FOR I=1 TO Cx+1
4110  Xat=Xmin*10^(I-1)
4115  IF I=Cx+1 THEN Nn=1
4120  FOR J=1 TO Nn
4125  IF J=1 THEN PRINT "TL 2 0"
4130  IF J=2 THEN PRINT "TL 1 0"
4135  Xa=Xat*J
4140  X=LGT(Xa/Xmin)*Sfx
4145  PRINT "PA";X," 0; XT;"
4150  NEXT J
4155  NEXT I
4160  PRINT "PA 100 0;PU;"
4165  PRINT "PU PA 0,0 PD"
4170  Nn=9
4175  FOR I=1 TO Cy+1
4180  Yat=Ymin*10^(I-1)
4185  IF I=Cy+1 THEN Nn=1
4190  FOR J=1 TO Nn
4195  IF J=1 THEN PRINT "TL 2 0"
4200  IF J=2 THEN PRINT "TL 1 0"
4205  Ya=Yat*J
4210  Y=LGT(Ya/Ymin)*Sfy
4215  PRINT "PA 0 ";Y "YT"
4220  NEXT J
4225  NEXT I
4230  PRINT "PA 0 100 TL 0 2"
4235  Nn=9
4240  FOR I=1 TO Cx+1
4245  Xat=Xmin*10^(I-1)
4250  IF I=Cx+1 THEN Nn=1
```

```
4255  FOR J=1 TO Nn
4260  IF J=1 THEN PRINT "TL 0 2"
4265  IF J>1 THEN PRINT "TL 0 1"
4270  Xa=Xat*J
4275  X=LGT(Xa/Xmin)*Sfx
4280  PRINT "PA";X,",100; XT"
4285  NEXT J
4290  NEXT I
4295  PRINT "PA 100,100 PU PA 100 0 PD"
4300  Nn=9
4305  FOR I=1 TO Cy+1
4310  Yat=Ymin*10^(I-1)
4315  IF I=Cy+1 THEN Nn=1
4320  FOR J=1 TO Nn
4325  IF J=1 THEN PRINT "TL 0 2"
4330  IF J>1 THEN PRINT "TL 0 1"
4335  Ya=Yat*J
4340  Y=LGT(Ya/Ymin)*Sfy
4345  PRINT "PD PA 100," Y,"YT"
4350  NEXT J
4355  NEXT I
4360  PRINT "PA 100,100 PU"
4365  PRINT "PA 0 -2 SR 1.5 2"
4370  Ii=LGT(Xmin)
4375  FOR I=1 TO Cx+1
4380  Xa=Xmin*10^(I-1)
4385  X=LGT(Xa/Xmin)*Sfx
4390  PRINT "PA";X,",0;"
4395  IF Ii>=0 THEN PRINT "CP -2,-2;LB10;PR -2,2;LB";Ii;""
4400  IF Ii<0 THEN PRINT "CP -2,-2;LB10;PR 0,2;LB";Ii;""
4405  Ii=Ii+1
4410  NEXT I
4415  PRINT "PU PA 0 0"
4420  Ii=LGT(Ymin)
4425  Y10=10
4430  FOR I=1 TO Cy+1
4435  Ya=Ymin*10^(I-1)
4440  Y=LGT(Ya/Ymin)*Sfy
4445  PRINT "PA 0,";Y,""
4450  PRINT "CP -4,-.25;LB10;PR -2,2;LB";Ii;""
4455  Ii=Ii+1
4460  NEXT I
4465  BEEP
4470  INPUT "WANT USE DEFAULT LABELS (1=Y,0=N)?",Idl
4475  IF Idl<>1 THEN
4480  BEEP
4485  INPUT "ENTER X-LABEL" Xlabel$
4490  BEEP
4495  INPUT "ENTER Y-LABEL",Ylabel$
4500  END IF
4505  IF Opo 2 THEN
4510  PRINT "SR 1,2;PU PA 40 -14;"
4515  PRINT "LB(T;PR -1.6,3 PD PR 1.2,0 PU;PR .5,-4;LBwo;PR .5,1;"
4520  PRINT "LB-T;PR .5,-1;LBsat;PR .5,1;"
4525  IF Iun=0 THEN
4530  PRINT "LB) (K)"
4535  ELSE
4540  PRINT "LB) (F)"
4545  END IF
4550  END IF
4555  IF Opo=2 THEN
4560  IF Iun=0 THEN
4565  PRINT "SR 1.5,2;PU PA 40,-14;LBq (W/m;SR 1,1.5;PR 0.5,1;LB2;SR 1.5,2;PR
0.5,-1;LB)"
4570  ELSE
4575  PRINT "SR 1.5,2;PU PA 34,-14;LBq (Btu/hr;PR .5,.5;LB.;PR .5,-.5;"
```

```
4580  PRINT "LBft;PR .5,1;SR 1,1.5;LB2;SR 1.5,2;PR .5,-1;LB);"
4585  END IF
4590  END IF
4595  IF Opo=0 THEN
4600  IF Iun=0 THEN
4605  PRINT "SR 1.5,2;PU PA -12,40;DI 0,1;LBq (W/m;PR -1,0.5;SR 1,1.5;LB2;SR 1
.5,2;PR 1,.5;LB)"
4610  ELSE
4615  PRINT "SR 1.5,2;PU PA -12,32;DI 0,1;LBq (Btu/hr;PR -.5,.5;LB.;PR .5,.5;"
4620  PRINT "LBft;SR 1,1.5;PR -1,.5;LB2;PR 1,.5;SR 1.5,2;LB)"
4625  END IF
4630  END IF
4635  IF Opo 0 THEN
4640  IF Iun=0 THEN
4645  PRINT "SR 1.5,2;PU PA -12,38;DI 0,1;LBh (W/m;PR -1,.5;SR 1,1.5;LB2;SR 1.
5,2;PR .5,.5;"
4650  PRINT "LB.;PR .5,0;LBK)"
4655  ELSE
4660  PRINT "SR 1.5,2;PU PA -12,28;DI 0,1;LBh (Btu/hr;PR -.5,.5;LB.;PR .5,.5;"
4665  PRINT "LBft;PR -1,.5;SR 1,1.5;LB2;SR 1.5,2;PR .5,.5;LB.;PR .5,.5;LBF)"
4670  END IF
4675  END IF
4680  IF Idl=0 THEN
4685  PRINT "SR 1.5,2;PU PA 50,-16 CP";-LEN(Xlabel$)/2;"0;LB";Xlabel$;""
4690  PRINT "PA -14,50 CP 0,";-LEN(Ylabel$)/2*5/6;"DI 0,1;LB";Ylabel$;""
4695  PRINT "CP 0,0 DI"
4700  END IF
4705  Ion=0
4710 Repeat:!
4715  Xll=1.E+6
4720  Xul=-1.E+6
4725  Icn=0
4730  BEEP
4735  INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Ok
4740  IF Ok=1 THEN
4745  BEEP
4750  INPUT "ENTER THE NAME OF THE DATA FILE",D_file$
4755  ASSIGN @File TO D_file$
4760  BEEP
4765  BEEP
4770  INPUT "ENTER THE BEGINNING RUN NUMBER",Md
4775  BEEP
4780  INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED",Npairs
4785  BEEP
4790  INPUT "CONNECT DATA WITH LINE (1=Y,0=N)?",Icl
4795  BEEP
4800  PRINTER IS 1
4805  PRINT USING "4X,""Select a symbol:"""
4810  PRINT USING "6X,""1  Star      2  Plus sign"""
4815  PRINT USING "6X,""3  Circle    4  Square"""
4820  PRINT USING "6X,""5  Rombus"""
4825  PRINT USING "6X,""6  Right-side-up triangle"""
4830  PRINT USING "6X,""7  Up-side-down triangle"""
4835  INPUT Sym
4840  PRINTER IS 705
4845  PRINT "PU DI"
4850  IF Sym=1 THEN PRINT "SM*"
4855  IF Sym=2 THEN PRINT "SM+"
4860  IF Sym=3 THEN PRINT "SMo"
4865  IF Md>1 THEN
4870  FOR I=1 TO (Md-1)
4875  ENTER @File;Ya,Xa
4880  NEXT I
4885  END IF
4890  FOR I=1 TO Npairs
4895  ENTER @File;Ya,Xa
```

```
4900  IF Opo=1 THEN Ya=Ya/Xa
4905  IF Opo=2 THEN
4910  Q=Ya
4915  Ya=Ya/Xa
4920  Xa=Q
4925  END IF
4930  IF Xa<Xll THEN Xll=Xa
4935  IF Xa>Xul THEN Xul=Xa
4940  IF Iun=1 THEN
4945  IF Ooo<2 THEN Xa=Xa*1.8
4950  IF Ooo>0 THEN Ya=Ya*.1761
4955  IF Ooo=0 THEN Ya=Ya*.317
4960  IF Ooo=2 THEN Xa=Xa*.317
4965  END IF
4970  X=LGT(Xa/Xmin)*Sfx
4975  Y=LGT(Ya/Ymin)*Sfy
4980  IF Sym<3 THEN PRINT "SM"
4985  IF Sym<4 THEN PRINT "SR 1.4,2.4"
4990  IF IcI=0 THEN
4995  PRINT "PA" X,Y,""
5000  ELSE
5005  PRINT "PA" X,Y,"PD"
5010  END IF
5015  IF Sym>3 THEN PRINT "SR 1.2,1.6"
5020  IF Sym=4 THEN PRINT "UC2.4,99,0,-8,-4,0,0,8,4,0;"
5025  IF Sym=5 THEN PRINT "UC3 0,99,-3,-6,-3,6,3,6,3,-6;"
5030  IF Sym=6 THEN PRINT "UC0.5.3,99,3,-8,-6,0,3,8;"
5035  IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8;"
5040  NEXT I
5045  PRINT "PU"
5050  BEEP
5055  ASSIGN @File TO *
5060  XII=XII/1.2
5065  Xul=XuI*1.2
5070! GOTO 8040
5075  END IF
5080  PRINT "PU SM"
5085  BEEP
5090  INPUT "WANT TO PLOT A POLYNOMIAL (1=Y,0=N)?",Go_on
5095  IF Go_on=1 THEN
5100  BEEP
5105  PRINTER IS 1
5110  PRINT USING "4X,""Select line type:"""
5115  PRINT USING "6X,""0      Solid line"""
5120  PRINT USING "6X,""1      Dashed"""
5125  PRINT USING "6X,""2,, 5 Longer line - dash"""
5130  INPUT Ion
5135  PRINTER IS 705
5140  BEEP
5145  INPUT "SELECT (0=LIN,1=LOG(X,Y))",Ilog
5150  Iornt=1
5155  CALL Poly
5160  FOR Xx=0 TO Cx STEP Cx/200
5165  Xa=Xmin*10^Xx
5170  IF Xa<XIl OR Xa>XuI THEN 5300
5175  Icn=Icn+1
5180  Pu=0
5185  IF Ion=1 THEN Idf=Icn MOD 2
5190  IF Ion=2 THEN Idf=Icn MOD 4
5195  IF Ion=3 THEN Idf=Icn MOD 8
5200  IF Ion=4 THEN Idf=Icn MOD 16
5205  IF Ion=5 THEN Idf=Icn MOD 28
5210  IF Idf=1 THEN Pu=1
5215  IF Ooo=0 THEN Ya=FNPoly(Xa)
5220  IF Ooo=2 AND Ilog=0 THEN Ya=Xa/FNPoly(Xa)
5225  IF Opo=2 AND Ilog=1 THEN Ya=FNPoly(Xa)
```

```
5230  IF Opo=1 THEN Ya=FNPoly(Xa)/Xa
5235  IF Ya<Ymin THEN 5300
5240  IF Iun=1 THEN
5245  IF Opo<2 THEN Xa=Xa*1.8
5250  IF Opo>0 THEN Ya=Ya*.1761
5255  IF Opo=0 THEN Ya=Ya*.317
5260  IF Opo=2 THEN Xa=Xa*.317
5265  END IF
5270  Y=LGT(Ya/Ymin)*Sfy
5275  X=LGT(Xa/Xmin)*Sfx
5280  IF Y<0 THEN Y=0
5285  IF Y>100 THEN GOTO 5300
5290  IF Pu=0 THEN PRINT "PA",X,Y,"PD"
5295  IF Pu=1 THEN PRINT "PA",X,Y,"PU"
5300  NEXT Xa
5305  PRINT "PU"
5310  END IF
5315  BEEP
5320  INPUT "WANT TO QUIT (1=Y,0=N)",Iqt
5325  IF Iqt=1 THEN 5335
5330  GOTO 4715
5335  PRINT "PU PA 0 0 SP0"
5340  SUBEND
5345  DEF FNHsmooth(X,Bop,Isat)
5350  DIM A(5),B(5),C(5),D(5)
5355  DATA .20526,.25322,.319048,.55322,.79909,1.00258
5360  DATA .74515,.72992,.73189,.71225,.68472,.64197
5365  DATA .41092,.17726,.25142,.54806,.81916,1.0845
5370  DATA .71403,.72913,.72565,.696691,.665867,.61889
5375  READ A(*),B(*),C(*),D(*)
5380  IF Bop<6 THEN I=Bop
5385  IF Bop=6 THEN I=4
5390  IF Bop=10 THEN I=5
5395  IF Isat=1 THEN
5400  Hs=EXP(A(I)+B(I)*LOG(X))
5405  ELSE
5410  Hs=EXP(C(I)+D(I)*LOG(X))
5415  END IF
5420  RETURN Hs
5425  FNEND
5430  DEF FNPoly(X)
5435  COM /Coly/ A(10,10),C(10),B(4),Nop,Iornt,Opo,Ilog
5440  X1=X
5445  Poly=B(0)
5450  FOR I=1 TO Nop
5455  IF Ilog=1 THEN X1=LOG(X)
5460  Poly=Poly+B(I)*X1^I
5465  NEXT I
5470  IF Ilog=1 THEN Poly=EXP(Poly)
5475  RETURN Poly
5480  FNEND
5485  SUB Poly
5490  DIM R(10),S(10),Sy(12),Sx(12),Xx(100),Yy(100)
5495  COM /Coly/ A(10,10),C(10),B(4),N,Iornt,Opo,Ilog
5500  COM /Xyy/ Xp(5),Yp(5)
5505  FOR I=0 TO 4
5510  B(I)=0
5515  NEXT I
5520  BEEP
5525  INPUT "SELECT (0=FILE,1=KEYBOARD,2=PROGRAM)",Im
5530  Im=Im+1
5535  BEEP
5540  INPUT "ENTER NUMBER OF X-Y PAIRS",No
5545  IF Im=1 THEN
5550  BEEP
5555  INPUT "ENTER DATA FILE NAME",D_file$
```

```
5560  BEEP
5565  INPUT "LIKE TO EXCLUDE DATA PAIRS (1=Y,0=N)?",Ied
5570  IF Ied=1 THEN
5575  BEEP
5580  INPUT "ENTER NUMBER OF PAIRS TO BE EXCLUDED",Ipex
5585  END IF
5590  ASSIGN @File TO D_file$
5595  ELSE
5600  BEEP
5605  INPUT "WANT TO CREATE A DATA FILE (1=Y,0=N)?",Yes
5610  IF Yes=1 THEN
5615  BEEP
5620  INPUT "GIVE A NAME FOR DATA FILE",D_file$
5625  CREATE BDAT D_file$ 5
5630  ASSIGN @File TO D_file$
5635  END IF
5640  END IF
5645  BEEP
5650  INPUT "ENTFR THE ORDER OF POLYNOMIAL",N
5655  FOR I=0 TO N*2
5660  Sy(I)=0
5665  Sx(I)=0
5670  NEXT I
5675  IF Ied=1 AND Im=1 THEN
5680  FOR I=1 TO Ipex
5685  ENTER @File;X,Y
5690  NEXT I
5695  END IF
5700  FOR I=1 TO Np
5705  IF Im=1 THEN
5710  IF Opo=2 THEN ENTER @File;X,Y
5715  IF Opo<>2 THEN ENTER @File;Y,X
5720  IF Ilog=1 THEN
5725  Xt=X/Y
5730  X=LOG(X)
5735  Y=LOG(Xt)
5740  END IF
5745  END IF
5750  IF Im=2 THEN
5755  BEEP
5760  INPUT "ENTER NEXT X-Y PAIR",X,Y
5765  IF Yes=1 THEN OUTPUT @File;X,Y
5770  END IF
5775  IF Im 3 THEN
5780  Xv(I)=X
5785  Yv(I)=Y
5790  ELSE
5795  X=Xp(I-1)
5800  Y=Yp(I-1)
5805  END IF
5810  R(0)=Y
5815  Sy(0)=Sy(0)+Y
5820  S(1)=X
5825  Sx(1)=Sx(1)+X
5830  FOR J=1 TO N
5835  R(J)=R(J-1)*X
5840  Sy(J)=Sy(J)+R(J)
5845  NEXT J
5850  FOR J=2 TO N*2
5855  S(J)=S(J-1)*X
5860  Sx(J)=Sx(J)+S(J)
5865  NEXT J
5870  NEXT I
5875  IF Yes=1 AND Im=2 THEN
5880  BEEP
5885  PRINT USING "12X,DD,"" X-Y pairs were stored in file "",10A";Np,D_file$
```

```
5890  END IF
5895  Sx(0)=No
5900  FOR I=0 TO N
5905  C(I)=Sy(I)
5910  FOR J=0 TO N
5915  A(I,J)=Sx(I+J)
5920  NEXT J
5925  NEXT I
5930  FOR I=0 TO N-1
5935  CALL Divide(I)
5940  CALL Subtract(I+1)
5945  NEXT I
5950  B(N)=C(N)/A(N,N)
5955  FOR I=0 TO N-1
5960  B(N-1-I)=C(N-1-I)
5965  FOR J=0 TO I
5970  B(N-1-I)=B(N-1-I)-A(N-1-I,N-J)*B(N-J)
5975  NEXT J
5980  B(N-1-I)=B(N-1-I)/A(N-1-I,N-1-I)
5985  NEXT I
5990 !PRINTER IS 701
5995 !PRINT B(*)
6000 !PRINTER IS 705
6005  IF Iprnt=0 THEN
6010  PRINT USING "12X,""EXPONENT     COEFFICIENT"""
6015  FOR I=0 TO N
6020  PRINT USING "15X,DD,5X,MD.7DE";I,B(I)
6025  NEXT I
6030  PRINT " "
6035  PRINT USING "12X,""DATA POINT       X              Y       Y(CALCULATED) DISCR
EPANCY"""
6040  FOR I=1 TO No
6045  Yc=B(0)
6050  FOR J=1 TO N
6055  Yc=Yc+B(J)*Xx(I)^J
6060  NEXT J
6065  D=Yy(I)-Yc
6070  PRINT USING "15X,3D,4X,4(MD.5DE,1X)";I,Xx(I),Yy(I),Yc,D
6075  NEXT I
6080  END IF
6085  ASSIGN @File TO *
6090  SUBEND
6095  SUB Divide(M)
6100  COM /Colv/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
6105  FOR I=M TO N
6110  Ao=A(I,M)
6115  FOR J=M TO N
6120  A(I,J)=A(I,J)/Ao
6125  NEXT J
6130  C(I)=C(I)/Ao
6135  NEXT I
6140  SUBEND
6145  SUB Subtract(K)
6150  COM /Colv/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
6155  FOR I=K TO N
6160  FOR J=K-1 TO N
6165  A(I,J)=A(K-1,J)-A(I,J)
6170  NEXT J
6175  C(I)=C(K-1)-C(I)
6180  NEXT I
6185  SUBEND
6190  SUB Flin
6195  COM /Colv/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
6200  COM /Xxyy/ Xx(5),Yy(5)
6205  PRINTER IS 705
6210  BEEP
```

```
6215  INPUT "SELECT (0=h/h0% same tube,1=h(HF)/h(sm)",Irt
6220  BEEP
6225  INPUT "WHICH Tsat (1=6.7,0=-2.2)",Isat
6230  Xmin=0
6235  Xmax=10
6240  Xstep=2
6245  IF Irt=0 THEN
6250  Ymin=0
6255  Ymax=1.4
6260  Ystep=.2
6265  ELSE
6270  Ymin=0
6275  Ymax=15
6280  Ystep=5
6285  END IF
6290  BEEP
6295  PRINT "IN;SP1;IP 2300,2200,8300,6900;"
6300  PRINT "SC 0,100,0 100;TL 2 0;"
6305  Sfx=100/(Xmax-Xmin)
6310  Sfy=100/(Ymax-Ymin)
6315  PRINT "PU 0,0 PD"
6320  FOR Xa=Xmin TO Xmax STEP Xstep
6325  X=(Xa-Xmin)*Sfx
6330  PRINT "PA";X,",0; XT;"
6335  NEXT Xa
6340  PRINT "PA 100,0;PU;"
6345  PRINT "PU PA 0,0 PD"
6350  FOR Ya=Ymin TO Ymax STEP Ystep
6355  Y=(Ya-Ymin)*Sfy
6360  PRINT "PA 0,";Y,"YT"
6365  NEXT Ya
6370  PRINT "PA 0,100 TL 0 2"
6375  FOR Xa=Xmin TO Xmax STEP Xstep
6380  X=(Xa-Xmin)*Sfx
6385  PRINT "PA";X,",100; XT"
6390  NEXT Xa
6395  PRINT "PA 100,100 PU PA 100,0 PD"
6400  FOR Ya=Ymin TO Ymax STEP Ystep
6405  Y=(Ya-Ymin)*Sfy
6410  PRINT "PD PA 100,",Y,"YT"
6415  NEXT Ya
6420  PRINT "PA 100,100 PU"
6425  PRINT "PA 0,-2 SR 1.5,2"
6430  FOR Xa=Xmin TO Xmax STEP Xstep
6435  X=(Xa-Xmin)*Sfx
6440  PRINT "PA";X,",0;"
6445  PRINT "CP -2,-1;LB";Xa;""
6450  NEXT Xa
6455  PRINT "PU PA 0,0"
6460  FOR Ya=Ymin TO Ymax STEP Ystep
6465  IF ABS(Ya)<1.E-5 THEN Ya=0
6470  Y=(Ya-Ymin)*Sfy
6475  PRINT "PA 0,";Y,""
6480  PRINT "CP -4,-.25;LB";Ya;""
6465  NEXT Ya
6490  Xlabel$="Oil Percent"
6495  IF Irt=0 THEN
6500  Ylabel$="h/h0%"
6505  ELSE
6510  Ylabel$="h/hsmooth"
6515  END IF
6520  PRINT "SR 1.5,2;PU PA 50 -10 CP";-LEN(Xlabel$)/2;"0;LB";Xlabel$;""
6525  PRINT "PA -11,50 CP 0,";-LEN(Ylabel$)/2*5/6;"DI 0,1;LB";Ylabel$;""
6530  PRINT "CP 0 0"
6535  Ipn=0
6540  BEEP
```

```
6545  INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Olo
6550  Icn=0
6555  IF Olo=1 THEN
6560  BEEP
6565  INPUT "ENTER THE NAME OF THE DATA FILE",O_file$
6570  BEEP
6575  INPUT "SELECT (0=LINEAR, 1=LOG(X,Y)",Ilog
6580  ASSIGN @File TO O_file$
6585  BEEP
6590  INPUT "ENTER THE BEGINNING RUN NUMBER",Md
6595  BEEP
6600  INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED",Npairs
6605  BEEP
6610  INPUT "ENTER DESIRED HEAT FLUX",Q
6615  BEEP
6620  PRINTER IS 1
6625  PRINT USING "4X,""Select a symbol:"""
6630  PRINT USING "4X,""1  Star    2  Plus sign"""
6635  PRINT USING "4X,""3  Circle 4  Square"""
6640  PRINT USING "4X,""5  Rombus"""
6645  PRINT USING "4X,""6  Right-side-up triangle"""
6650  PRINT USING "4X,""7  Up-side-down triangle"""
6655  INPUT Sym
6660  PRINTER IS 705
6665  PRINT "PU OI"
6670  IF Sym=1 THEN PRINT "SM*"
6675  IF Sym=2 THEN PRINT "SM+"
6680  IF Sym=3 THEN PRINT "SMo"
6685  Nn=4
6690  IF Ilog=1 THEN Nn=1
6695  IF Md>1 THEN
6700  FOR I=1 TO (Md-1)
6705  ENTER @File;Xa,Ya
6710  NEXT I
6715  END IF
6720  OI=O
6725  IF Ilog=1 THEN Q=LOG(Q)
6730  FOR I=1 TO Npairs
6735  ENTER @File;Xa,B(*)
6740  Ya=B(0)
6745  FOR K=1 TO Nn
6750  Ya=Ya+B(K)*Q^K
6755  NEXT K
6760  IF Ilog=1 THEN Ya=EXP(Ya)
6765  IF Ilog=0 THEN Ya=Q1/Ya
6770  IF Irt=0 THEN
6775  IF Xa=0 THEN
6780  Yo=Ya
6785  Ya=1
6790  ELSE
6795  Ya=Ya/Yo
6800  END IF
6805  ELSE
6810  Hsm=FNHsmooth(Q,Xa,Isat)
6815  Ya=Ya/Hsm
6820  END IF
6825  Xv(I-1)=Xa
6830  Yv(I-1)=Ya
6835  X=(Xa-Xmin)*Sfx
6840  Y=(Ya-Ymin)*Sfy
6845  IF Sym>3 THEN PRINT "SM"
6850  IF Sym>4 THEN PRINT "SR 1.4,2.4"
6855  PRINT "PA",X,Y,""
6860  IF Sym>3 THEN PRINT "SR 1.2,1.6"
6865  IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0;"
6870  IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6;"
```

```
6875  IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6.0,3.8;"
6880  IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8.6,0,-3.-8;"
6885  NEXT I
6890  BEEP
6895  ASSIGN @File TO *
6900  END IF
6905  PRINT "PU SM"
6910  BEEP
6915  INPUT "WANT TO PLOT A POLYNOMIAL (1=Y,0=N)?",Okp
6920  IF Okp=1 THEN
6925  BEEP
6930  INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
6935  Iornt=1
6940  CALL Poly
6945  FOR Xa=Xmin TO Xmax STEP Xstep/25
6950  Icn=Icn+1
6955  Ya=FNPoly(Xa)
6960  Y=(Ya-Ymin)*Sfy
6965  X=(Xa-Xmin)*Sfx
6970  IF Y<0 THEN Y=0
6975  IF Y>100 THEN GOTO 7025
6980  Pu=0
6985  IF Ion=1 THEN Idf=Icn MOD 2
6990  IF Ion=2 THEN Idf=Icn MOD 4
6995  IF Ion=3 THEN Idf=Icn MOD 8
7000  IF Ion=4 THEN Idf=Icn MOD 16
7005  IF Ion=5 THEN Idf=Icn MOD 32
7010  IF Idf=1 THEN Pu=1
7015  IF Pu=0 THEN PRINT "PA",X,Y,"PD"
7020  IF Pu=1 THEN PRINT "PA",X,Y,"PU"
7025  NEXT Xa
7030  PRINT "PU"
7035  Ipn=Ion+1
7040  GOTO 6540
7045  END IF
7050  BEEP
7055  INPUT "WANT TO QUIT (1=Y,0=N)?",Iquit
7060  IF Iquit=1 THEN 7070
7065  GOTO 6540
7070  PRINT "PU SP0"
7075  SUBEND
7080  SUB Stats
7085  PRINTER IS 701
7090  J=0
7095  K=0
7100  BEEP
7105  INPUT "PLOT FILE TO ANALYZE?",File$
7110  ASSIGN @File TO File$
7115  BEEP
7120  INPUT "LAST RUN No?(0=QUIT)",Nn
7125  IF Nn=0 THEN 7305
7130  Nn=Nn-J
7135  Sx=0
7140  Sy=0
7145  Sz=0
7150  Sxs=0
7155  Sys=0
7160  Szs=0
7165  FOR I=1 TO Nn
7170  J=J+1
7175  ENTER @File;Q,T
7180  H=Q/T
7185  Sx=Sx+Q
7190  Sxs=Sxs+Q^2
7195  Sy=Sy+T
7200  Sys=Sys+T^2
```

```
7205  Sz=Sz+H
7210  Szs=Szs+H^2
7215  NEXT I
7220  Qave=Sx/Nn
7225  Tave=Sy/Nn
7230  Have=Sz/Nn
7235  Sdevq=SQR(ABS((Nn*Sxs-Sx^2)/(Nn*(Nn-1))))
7240  Sdevt=SQR(ABS((Nn*Sys-Sy^2)/(Nn*(Nn-1))))
7245  Sdevh=SQR(ABS((Nn*Szs-Sz^2)/(Nn*(Nn-1))))
7250  Sh=100*Sdevh/Have
7255  Sq=100*Sdevq/Qave
7260  St=100*Sdevt/Tave
7265  IF K=1 THEN 7295
7270  PRINT
7275  PRINT USING "11X,""DATA FILE:"",14A";File$
7280  PRINT
7285  PRINT USING "11X,""RUN Htube      SdevH   Qdp          SdevQ   Thetab SdevT"""
7290  K=1
7295  PRINT USING "11X,DD,2(2X,D.3DE,1X,3D.2D),2X,DD.3D,1X,3D.2D";J,Have,Sh,Qave
,Sq,Tave,St
7300  GOTO 7115
7305  ASSIGN @File1 TO *
7310  PRINTER IS 1
7315  SUBEND
7320  SUB Coef
7325  COM /Colv/ A(10,10),C(10),B(4),N,Iprnt,Qpo,Ilog
7330  BEEP
7335  INPUT "GIVE A NAME FOR CROSS-PLOT FILE",Cpf$
7340  CREATE BDAT Cpf$,2
7345  ASSIGN @File TO Cpf$
7350  BEEP
7355  INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
7360  BEEP
7365  INPUT "ENTER OIL PERCENT (-1=STOP)",Bop
7370  IF Bop<0 THEN 7390
7375  CALL Poly
7380  OUTPUT @File;Bop,B(*)
7385  GOTO 7360
7390  ASSIGN @File TO *
7395  SUBEND
```

APPENDIX C
COMPUTER-CONTROLLED VALVE PROGRAM

The computer-controlled valve was controlled by an Octagon Systems SYS-2A microcontroller. The SYS-2A is a complete computer system on a single card and requires only a 5 volt supply for operation. The SYS-2A has provisions for 4, 2.5 volt A/D data inputs and 8 high current digital outputs. The card was configured as shwon in Table 4 below.

TABLE 4
Configuration of SYS-2A I/O Channels

Data Input Channel	Purpose
@#A10 = 8	Valve position
@#A10 = 9	Liquid R-114 Temperature

Data Output Channel	Purpose
@#A00	Shut Valve Relay (0=stop,1=shut)
@#A01	Open Valve Relay (0=stop,1=open)

The proportional-integral-derivative control program below was written in NSC "tiny BASIC." The SYS-2A microcontroller operator's manual includes an appendix of tiny BASIC commands. Remarks are provided below that were not in the actual program (to minimize execution time) for clarity. The program was stored in EEPROM added to the card after program debugging was complete.

```
10 Let A=15:Let B=5:Let C=10:Let F=0:Let I=0  Initialize
15 Let @#A00=0:Let @#A01=0                    Stop Valve
20 Print"Set Constants(1=Y,0=N)?":Input Q
30 If(Q=0)then GOTO 60
40 Print"A,B,C,G?":Input H,J,K,L
50 Let A=H:Let B=J:Let C=K:Let G=L
60 Print"Input Desired Temp(-1=End)":Input R    Enter Temp
```

```
70 Let @#A10=9:Delay 2:Let M=16*@#A11+@#A12/16  Read Channel 9
80 Let @#A10=8:Delay 2:Let P=16*@#A11+@#A12/16  Read Channel 8
90 Print"Temp=",M,"Pos=",P
100 If(R<0)then GOTO 800                        Exit Program
200 Let @#A10=8:Delay 2:Let P=16*@#A11+@#A12/16 Read Channel 8
210 Let S=0                                     Ave 10 Readings
220 For N=1 to 10 Step 1
230 Let @#A10=9:Delay 2:Let M=16*@#A11+@#A12/16 Read Temp
240 Let E=M-R:Let S=S+E                         Error;average
250 Next N
260 Let E=S:Let D=S-F:Let F=E                   Error;Derivative
262 If(E<0)then I=I-1                           Integral
264 If(E>0)then I=I+1                           Integral
266 If(I<-31000)then I=-31000                   Binary Limit
268 If(I>31000)then I=31000                     Binary Limit
270 Print"M=",M,"E=",E,"D=",D,"I=",I
300 If(E<-1000)then GOTO 600                    Control Band
310 If(E>2000)then GOTO 700                     Control Band
400 Let V=(E/A)+(B*D)+(I/C)                     PID Value
410 Print"V=",V,"ET=",E/A,"DT=",B*D,"IT=",I/C    Debug Tool
420 If(V>0)then GOTO 500                        Above Desired
430 Let V=V*(-1)*G                              Shut Faster
440 If(V<1)then V=1                             Check
450 If(V>1040)then V=0   Delay Function limited 1-1040 entry
460 If(P<150)then V=15   Slow Valve near end of travel
465 If(P<50)then V=10
470 If(P<20)then GOTO 200   End of Travel Limit
480 Let @#A00=1:Delay(V):Let @#A00=0       Shut Variable Time
490 GOTO 200
500 If(P<2500)then GOTO 200   End of Travel Limit
510 If(V<1)then V=1       Check
520 If(V>1040)then V=0   Delay Function limited 1-1040 entry
530 Let @#A01=1:Delay(V):Let @#A01=0       Open Variable Time
540 GOTO 200
600 If(P<20)then GOTO 200   End of Travel Limit
```

```
610 Print"600 Loop"          Out of Bound Warning
620 Let V=0                  Max valve shutting speed
630 If(P<250)then V=50       Slow near end of travel limit
640 If(P<150)then V=15
645 If(P<50)then V=10
650 Let @#A00=1:Delay(V):Let @#A00=0        Shut Valve Fully
660 Let @#A10=8:Delay 2:Let P=16*@#A11+@#A12/16 Read Channel 8
670 GOTO 600
700 If(P>2500)then GOTO 200   End of Travel Limit
710 Print"700 Loop"           Out of Bound Warning
720 Let @#A01=1:Delay 0:Let @#A01=1           Open Valve Fully
730 Let @#A10=8:Delay 2:Let P=16*@#A11+@#A12/16 Read Channel 8
740 GOTO 700
800 END
```

APPENDIX D

EXAMPLES OF REPRESENTATIVE DATA RUNS

The two printouts below are samples of the output of DRP2. The first printout (WH79) is for the smooth tube at high heat flux with 0 percent oil. The second printout (HF101) is for the High Flux tube under similiar conditions.

```
Month, date and time :03:25:10:02:18

NOTE: Program name : DRP2
      Disk number  = 02
      Old file name: WH79
      This data set taken on : 02:10:12:50:15
      Tube Type:      4

Data Set Number =   1  Bulk Oil % =  0.0      02:10:13:16:18

TC No:     1       2       3       4       5       6       7       8
Temp :   16.42   14.69   14.61   15.00   14.67   14.91   16.79   14.74
 Twa     Tliqd   Tliqd2  Tvapr   Psat    Tsump
 15.23   -2.26   -2.20    -.63   -6.31   -17.7
 Thetab  Htube        Qdp
 16.935  5.704E+03   9.660E+04

Data Set Number =   2  Bulk Oil % =  0.0      02:10:13:19:35

TC No:     1       2       3       4       5       6       7       8
Temp :   16.48   14.60   14.54   14.93   14.52   14.74   16.69   14.67
 Twa     Tliqd   Tliqd2  Tvapr   Psat    Tsump
 15.15   -2.27   -2.10   -1.44   -6.32   -17.1
 Thetab  Htube        Qdp
 16.866  5.745E+03   9.689E+04

Data Set Number =   3  Bulk Oil % =  0.0      02:10:13:19:56

TC No:     1       2       3       4       5       6       7       8
Temp :   16.48   14.56   14.52   14.95   14.50   14.67   16.62   14.67
 Twa     Tliqd   Tliqd2  Tvapr   Psat    Tsump
 15.12   -2.27   -2.13   -1.51   -6.32   -17.0
 Thetab  Htube        Qdp
 16.840  5.760E+03   9.701E+04
NOTE: 03 X-Y pairs were stored in plot data file PWH79

 DATA FILE:PWH79

 RUN Htube      SdevH   Qdp         SdevQ   Thetab  SdevT
  3  5.736E+03    .51   9.683E+04     .22   16.880    .29
```

```
Month, date and time :03:25:10:03:26

NOTE: Program name : DRP2
      Disk number  = 02
      Old file name: HF101
      This data set taken on : 02:16:19:06:52
      Tube Type:      5

Data Set Number =    1  Bulk Oil % =  0.0      02:16:19:31:02

TC No:     1       2       3       4       5       6       7       8
Temp :    5.52    2.63    3.76    4.57    3.93    4.52    7.31    4.17
 Twa     Tliqd    Tliqd2  Tvapr   Psat    Tsump
  4.55  -2.14    -1.87      .37  -6.20  -15.7
 Thetab  Htube         Qdo
  3.370  2.801E+04   9.440E+04

Data Set Number =    2  Bulk Oil % =  0.0      02:16:19:31:16

TC No:     1       2       3       4       5       6       7       8
Temp :    5.54    2.65    3.76    4.57    3.93    4.53    7.31    4.18
 Twa     Tliqd    Tliqd2  Tvapr   Psat    Tsump
  4.56  -2.14    -1.90      .32  -6.20  -15.6
 Thetab  Htube         Qdo
  3.379  2.792E+04   9.433E+04

Data Set Number =    3  Bulk Oil % =  0.0      02:16:19:31:27

TC No:     1       2       3       4       5       6       7       8
Temp :    5.55    2.63    3.76    4.57    3.93    4.53    7.31    4.17
 Twa     Tliqd    Tliqd2  Tvapr   Psat    Tsump
  4.56  -2.14    -1.91      .26  -6.20  -15.5
 Thetab  Htube         Qdo
  3.369  2.807E+04   9.456E+04
NOTE: 03 X-Y pairs were stored in plot data file PHF101

 DATA FILE:PHF101

 RUN Htube      SdevH    Qdo          SdevQ    Thetab SdevT
  3  2.800E+04    .27   9.443E+04     .12    3.373    .16
```

APPENDIX E
UNCERTAINTY ANALYSIS

The uncertainty of the heat-transfer coefficient at 37 kW/m^2 and 5 kW/m^2 of runs WH79 and HF101 are analyzed below. The analysis is based on the Kline-McClintock [Ref. 24] method of uncertainty analysis.

The heat-transfer coefficient is:

$$h = \frac{q_c}{\bar{T}_{wo} - T_{sat}} \tag{E.1}$$

and

$$\bar{T}_{wo} - T_{sat} = \bar{T}_{wi} - \frac{Q_c \, \ln (D_2/D_1)}{2 \pi k L} - T_{sat} \tag{E.2}$$

where

h = heat-transfer coefficient

q_c = heat flux corrected for end losses

$\bar{T}_{wo}$ = average outer wall temperature

T_{sat} = saturation temperature

$\bar{T}_{wi}$ = average inner wall temperature

Q_c = heat input corrected for end losses

D_2 = outer wall diameter of tube

D_1 = inner wall diameter of tube

k = thermal conductivity of wall

L = length of heated surface

let

$$F = \frac{Q_c \, \ln (D_2/D_1)}{2 \pi k L} \tag{E.3}$$

According to Kline and McClintock, the uncertainty in the heat-transfer coefficient is:

$$\frac{\delta h}{h} = \left[\left(\frac{\delta q_c}{q_c}\right)^2 + \left(\frac{\delta \bar{T}_{wi}}{\bar{T}_{wo} - T_{sat}}\right)^2 + \right. \tag{E.4}$$

$$\left.\left(\frac{\delta F}{\bar{T}_{wo} - T_{sat}}\right)^2 + \left(\frac{\delta T_{sat}}{\bar{T}_{wo} - T_{sat}}\right)^2\right]^{1/2}$$

by neglecting the error from the logarithmic term, because it is small compared to the other terms, the uncertainty of the Fourier term (F) can be estimated as:

$$\delta F \approx F \left[\left(\frac{\delta Q_c}{Q_c}\right)^2 + \left(\frac{\delta k}{k}\right)^2 + \left(\frac{\delta L}{L}\right)^2\right]^{1/2} \tag{E.5}$$

and

$$Q_c = q_c \, \pi \, D_2 \, L \tag{E.6}$$

which has an uncertainty of

$$\frac{\delta Q_c}{Q_c} = \left[\left(\frac{\delta q_c}{q_c}\right)^2 + \left(\frac{\delta D_2}{D_2}\right)^2 + \left(\frac{\delta L}{L}\right)^2\right]^{1/2} \tag{E.7}$$

Table 5 lists the various terms of equations (E.1) through (E.7) assuming all 8 wall thermocouples are used to get the average wall temperature $\bar{T}_{wi}$. The data-reduction program (DRP2) used this method to calculate the heat-transfer

TABLE 5

Uncertainty Analysis Terms Using 8 Thermocouples

File Heat Flux	WH79 37 kW/m^2	WH79 5 kW/m^2	HF101 37 kW/m^2	HF101 5 kW/m^2
$\frac{\delta Q_c}{Q_c}$	0.007	0.009	0.006	0.007
$\frac{\delta k}{k}$	0.15	0.15	0.33	0.33
$\frac{\delta L}{L}$	0.0005	0.0005	0.0005	0.0005
F term (°C)	0.201	0.024	1.316	0.170
δF (°C)	0.030	0.004	0.434	0.056
$\bar{T}_{wi}$ (°C)	11.46	5.63	0.79	-1.43
T_{sat} (°C)	-2.21	-2.23	-2.21	-2.18
$\frac{\delta \bar{T}_{wi}}{\bar{T}_{wo} - T_{sat}}$	0.032	0.073	0.290	0.126
$\frac{\delta F}{\bar{T}_{wo} - T_{sat}}$	0.002	0.0005	0.259	0.097
$\frac{\delta T_{sat}}{\bar{T}_{wo} - T_{sat}}$	0.003	0.008	0.015	0.019
$\frac{\delta q_c}{q_c}$	0.003	0.007	0.008	0.003
$\frac{\delta h}{h}$	0.032	0.074	0.389	0.160
h (W/m^2 K)	2660	540	22300	8400

coefficient. Table 6 lists the same terms assuming only the center 4 wall thermocouples (2, 3, 5, and 6) are used to calculate the heat-transfer coefficient. Comparing Tables 5 and 6 shows the effect of the axial and circumferential wall temperature distributions on the uncertainty of the heat-transfer coefficient.

The constraining error of the smooth tube is the uncertainty in the wall temperature. Removing the effect of the axial wall temperatue distribution reduces the uncertainty by 1 percent. The large wall superheat of the smooth tube contributes to the small magnitude of the uncertainty terms. The constraining error of the High Flux tube is also the uncertainty in the wall temperature, but the uncertainty of the thermal conductivity (part of the F term) is about the same magnitude an results in the larger overall uncertainty of the High Flux data. The small wall superheats of the High Flux tube also amplify the magnitudes of uncertainty terms. Removing the effect of the axial wall temperature distribution makes the uncertainty in the thermal conductivity of the copper-nickel High Flux tube the constraining uncertainty. The axial temperature distribution is responsible for about 25 percent of the wall uncertainty term, but again the combined effect of the uncertainty of the thermal conductivity, and low wall superheats, does not make it wholely responsible for the large uncertainty of the High Flux data. More accurate data could be obtained on the High Flux surface by using a solid copper tube without a large uncertainty in the wall resistance or an axial wall temperature variation.

TABLE 6

Uncertainty Analysis Terms Using Center 4 Thermocouples

File Heat Flux	WH79 37 kW/m^2	WH79 5 kW/m^2	HF101 37 kW/m^2	HF101 5 kW/m^2
$\frac{\delta Q_c}{Q_c}$	0.007	0.009	0.006	0.007
$\frac{\delta k}{k}$	0.15	0.15	0.33	0.33
$\frac{\delta L}{L}$	0.0005	0.0005	0.0005	0.0005
F term (^oC)	0.201	0.024	1.316	0.170
δF (^oC)	0.030	0.004	0.434	0.056
$\overline{T}_{wi}$ (^oC)	11.34	5.80	0.44	-1.49
T_{sat} (^oC)	-2.21	-2.23	-2.21	-2.18
$\frac{\delta \overline{T}_{wi}}{\overline{T}_{wo} - T_{sat}}$	0.015	0.063	0.213	0.097
$\frac{\delta F}{\overline{T}_{wo} - T_{sat}}$	0.002	0.0004	0.325	0.108
$\frac{\delta T_{sat}}{T_{wo} - T_{sat}}$	0.003	0.008	0.019	0.021
$\frac{\delta q_c}{q_c}$	0.003	0.007	0.008	0.003
$\frac{\delta h}{h}$	0.016	0.064	0.389	0.146
h (W/m^2 K)	2690	530	27800	9280

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